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PERFORMANCE ASSESSMENT OF ELEMENT FORMULATIONS AND CONSTITUTIVE LAWS FOR THE SIMULATION OF INCREMENTAL SHEET FORMING (ISF)

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Summary. *The work detailed in this paper describes a new method allowing (i) displacements and strains of arbitrary magnitude to be recorded in-process during incremental sheet forming and (ii) to quantitatively correlate these data with corresponding finite element calculations. Initial tests were condcuted assessing the performance of different element formulations and constitutive laws in the context of incremental sheet forming.*

1 INTRODUCTION

Incremental sheet forming (ISF) is a sheet forming process that uses principles of layered manufacturing to produce sheet metal parts [1]: the part's geometry is split into a series of 2D layers, and the plastic deformation is carried out layer-by-layer through the CNC controlled movements of a simple forming tool. The deformation involves large plastic strains (logarithmic strains of up to 1.8) of a thin metal sheet under cyclic loading conditions. In the FEA, this demands efficient element formulations, constitutive laws and reliable material input data covering the whole range of plastic strains. The present paper deals with a new measurement technique allowing for a quantitative experimental validation of finite element analyses of ISF. In particular, the performance of different element formulations and constitutive laws is assessed.

2 BENCHMARK FORMING OPERATION

The forming of an axisymmetric cup made of 1.5 mm DC04 has been chosen as a benchmark. The tool path for this experiment is depicted in figure 1. It describes a cone opening up from 0 mm diameter at z = 0 mm to 115 mm at z = - 25 mm. During forming, the sheet rests on a 6 mm thick steel backing plate with a circular hole of 120 mm diameter. The tool path consists of five circles with a vertical pitch of 5 mm in-between.

3 QUANTITATIVE EXPERIMENTAL VALIDATION

Optical deformation measurement allows the deformation of the sheet metal to be recorded online during forming. In order to track the movement of material points, a

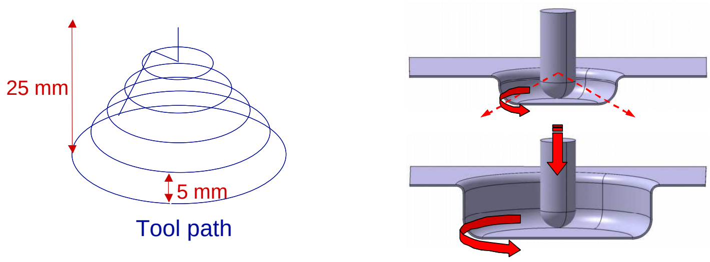

Figure 1: Benchmark part

stochastic black-and-white spray pattern is applied to the sheet's surface prior to forming. A software package defines facets on the pattern which are recognised during all recorded load stages. The software then computes the 3D displacements of all facet centres. Deformation measures can be obtained from the displacement field in a straightforward manner. However, the large strains present in ISF cause the paint to deteriorate, allowing direct measurements of the deformation only in an initial stage of the process.

3.1 ENHANCEMENTS TO THE MEASUREMENT TECHNIQUE

To enable strain measurements at high plastic strains, a new evaluation procedure has been implemented. Here, the deformation is recorded up to a stage of the process where the pattern is still intact. The user can check the quality of the pattern online through the photogrammetry software and decide whether the pattern has begun to lose its ability to track the deformation. Then, the process is halted, the initial black-and-white spray pattern is removed, and a new pattern is applied to the surface of the sheet. This can be done without dismounting the part. Due to the CNC contolled forming the process can be resumed at exactly the same position where it was halted. This procedure can be compared to a remeshing in finite element simulations. In order to trace the motion of nodes throughout the whole process, the data must be transferred from the old "mesh" to the new "mesh" whenever a new pattern is applied. To this end, add-ons to the original software were developed. First, a triangular mesh is defined upon the facets of the undeformed part. Whenever a new pattern is applied, a new triangular mesh is defined based upon the new set of recognised points/facets. For the data transfer, the displacments are treated as nodal values and transfered from the old mesh to the new mesh using shape functions of constant strain triangles. The method has been tested in the medium strain range. A complete forming process has been recorded once using a single pattern, and once with a two–stage evaluation using two patterns. The outcomes of both evaluation routes are in good agreement in the area for which the view angles and the focal lengths of the cameras are adjusted (see figure 2, red-marked areas).

3.2 QUANTITATIVE COMPARISON OF FEA AND EXPERIMENTS

A method to quantitatively validate FEA and experiments has been developed by the authors [1]. This method allows for a quantitative comparison of FEA and related exper-

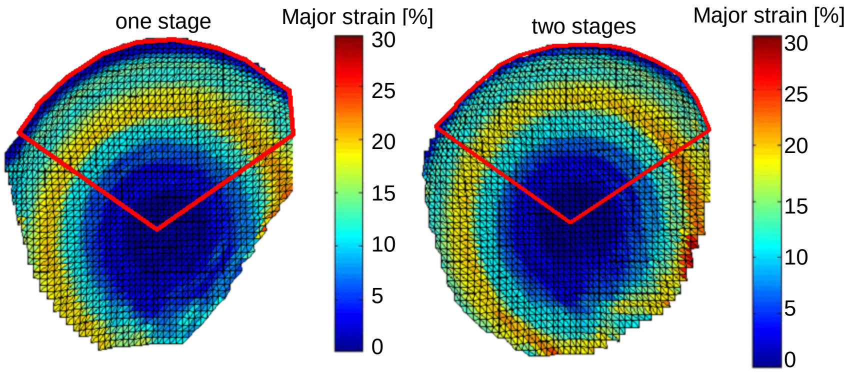

Figure 2: Comparison of a single-stage and two-stage deformation measurement

imental data using (i) synchronised frames of reference and (ii) a spatial and temporal synchronization of the tool movement. (i) is achieved by the determination of the tool center point coordinates for three non-collinear tool positions through the image processing software. (ii) is realised by a preprocessing routine that translates the NC code into ABAQUS input file format (spatial synchronisation), allowing for the addition of trigger points to compare measurements and FEA results at precisely determined stages of the process (temporal synchronisation).

4 PERFORMANCE OF ELEMENTS AND CONSTITUTIVE LAWS

Finite element calculations were conducted for the benchmark part, varying both the types of elements and the constitutive laws. The in-plane discretisation was kept constant for all element types. Two elements over the sheet thickness were used in the analyses involving solid elements. For a quantitative performance assessment, both displacement fields and strains were determined experimentally by applying the measuring techniques described in the foregoing paragraphs.

Influence of constitutive law. Computations have been performed using (i) von-Mises plasticity with isotropic hardening, (ii) von-Mises plasticity with combined isotropic and kinematic hardening and (iii) Hill'48 plasticity with isotropic hardening. Almost no difference was found between the outcome of the analyses using von-Mises and Hill'48 plasticity. However, the geometry of the part can be better predicted when kinematic hardening is accounted for (figure 3).

Influence of element formulation. Different element formulations were tested for the benchmark configuration. Table 1 gives details of the performance regarding the prediciton of geometry (maximum ($\Delta_{d,max}$) and average ($\Delta_{d,av}$) deviation from experimental data) and sheet thickness (max. deviation Δ_{th}). See [2] for details on the element implementation. The best performance was achieved using (plane-stress) shell elements, despite the fact that a 3D state of stress should be present in the plastic zone under the tool. The use of solid elements results in a considerable increase of CPU time. Therefore, no more than two elements were used over the sheet thickness. With these settings, reduced

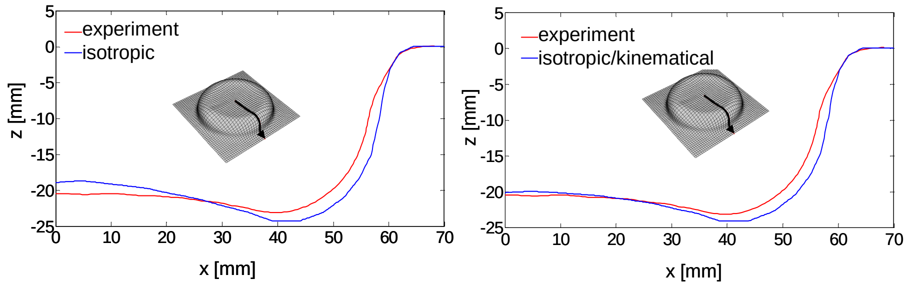

Figure 3: Prediction of the geometry with and without kinematic hardening.

Element	$\Delta_{d,max}[mm]$	$\Delta_{d,av}[mm]$	$\Delta_{th}[\%]$	CPU time [h]
C3D8	2.59	1.54	14.52	17.6
C3D8R	6.35	3.56	15.09	15.4
C3D8R enh.	2.04	1.07	14.23	28.3
C3D8H	2.25	1.54	16.65	48.1
C3D8I	2.18	1.19	17.08	34.9
C3D8IH	2.17	1.07	17.07	103.3
C3D8RH	6.37	3.56	15.29	50.9
S4R	1.09	0.59	11.72	7.3

Table 1: Element performance: C3D8X are solid elements, S4R is a shell element. Notation: see [2].

integrated solids with an hourglass control based on enhanced assumed strains give the best overall performance with respect to accuracy and computational costs.

5 SUMMARY AND OUTLOOK

The present paper deals with a method to quantitatively validate finite element analyses using optical deformation measurement. A performance assessment of elements and constitutive laws in the context of FEA for incremental sheet forming was conducted as an initial application. Future work will focus on reverse engineering applications to determine material and frictional properties for ISF.

6 ACKNOWLEDGEMENTS

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