THE SIGNIFICANCE OF FRICTION IN THE SINGLE POINT INCREMENTAL FORMING PROCESS

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ABSTRACT: The Single Point Incremental Forming Process (SPIF) makes use of a single, small forming tool to incrementally deform a metal sheet into a complex shape. Without a need for dedicated tooling, this process meets the demand for small batch production and Rapid Prototyping of industrial shell-like structures. The sheet is formed due to a locally applied stress field on its surface, consisting of a normal and a shear component. The shear component is strongly influenced by friction with the dragging forming tool. In common practice, SPIF is performed under well lubricated conditions and with tool rotation, both designed to minimize friction. Through-Thickness Shear (TTS), which is part of the deformation mechanism in SPIF, may be intuitively linked to the friction applied during the process.
In this paper, the role of friction in SPIF is experimentally investigated through the forming of an aluminium alloy sheet (AA3103-O) into a large wall angle cone with and without imposed tool rotation. It is found that *only* the force component along the instantaneous tool movement direction depends on the tool rotation, i.e. on the friction conditions. Finite Element (FE) simulations are also presented, which use (i) continuum elements, so that TTS can be taken into account, (ii) a sub-millimetre FE mesh, so that the small contact zone may be adequately modelled, and (iii) a mixed isotropic-kinematic hardening law that captures the anisotropic hardening until large strains. Under these three conditions, a quite accurate prediction of the forming force is obtained. Furthermore, it is shown how the validation of the FE constitutive law may be decoupled from the validation of the FE contact model. Finally, it is seen that overall TTS predictions are affected by tool rotation, which shows that the deformation mechanism in SPIF may be controlled to a certain extent by the imposed tool rotation.

KEYWORDS: Single Point Incremental Forming, Finite Element Modeling, Friction

1 INTRODUCTION

Recent experimental studies have shown the existence of Through-Thickness Shear (TTS) in SPIF-formed products [1-2]. The adopted FE strategy allows to capture TTS as well as the small contact zone under the forming tool, using a sub-millimetre mesh at reasonable computational cost as in [3-4]. Furthermore, an advanced material law is adopted featuring mixed isotropic-kinematic hardening, the coefficients of which are obtained from an inverse modelling procedure designed for FE models of SPIF [5-7]. Only the material model which results in the most accurate forming force obtained in [7], is presently considered.

2 EXPERIMENT

The present study focuses on the SPIF process based on a unidirectional tool-path strategy of contours and step-downs, to obtain a truncated cone of wall angle α=60°. The 1.2mm thick sheet, a Fe-Mn-alloyed aluminium in the annealed state (AA3003-O), is fully clamped to a backing plate with a circumferential orifice of radius r_b=91mm. The forming tool is fabricated out of tungsten carbide with TiN coating and has a hemispherical shape with diameter d_t=10mm. It is mounted on a converted three-axis ACIERA milling machine, following a programmed tool path that is most conveniently described for a cone geometry by a (fixed) cylindrical reference frame R-Θ-Z. The tool path consists out of circular contours with diminishing radii in a constant Z-plane, alternated by a step-down of magnitude Δz=0.744mm in the Z-direction, for a total number of 50 contours. The contour radii are chosen such that a (maximal) inner cone radius r_c=75mm is obtained.
In the experimental set-up, oil lubrication is applied to the sheet-tool contact throughout the process. Besides an imposed speed v_t=2000mm/min of the tool centre, a spindle speed ω_t (around the Z-axis) may also be imposed onto the tool. It is a common practice in SPIF to impose a spindle speed that establishes a rolling contact at an intermediate point along the theoretical cone wall contact zone [8], with the aim to further reduce friction. For the present process conditions, this leads to a spindle speed ω_t=2.45rev/s (called 'ToolRot' further on). Also the case ω_t=0rev/s ('NO_ToolRot') is considered in a separate experiment.

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3 FINITE ELEMENT SIMULATION

3.1 FE SUB-MODELLING TECHNIQUE

In order to achieve a high mesh density in the small plastic zone under the SPIF forming tool at a reasonable computational cost, two FE models, shown in Figure 1, are solved serially in time. The commercial implicit FE software ABAQUS/STANDARD (v.6.6-1) is used.

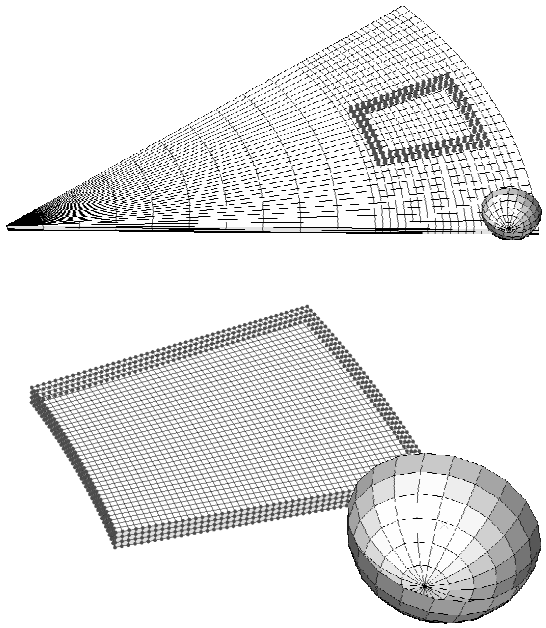


Figure 1: FE mesh of (top) the global model (G) and (bottom) the large sub-model (S1)

The first FE model is referred to as the 'global model' *G*. By modelling only a sheet section of 40° in the Θ-direction and using a relative coarse mesh (1.3mm characteristic element size), its simulation time is kept reasonably low. Nodes on the periphery are fully constrained to model the sheet clamping. At the two artificially created edges of the global model (Θ=0°- and 40°-sections), non-physical symmetry boundary (BC's) conditions are imposed as crude approximations.

Only a small piece of the unclamped sheet is considered in the 'large sub-model' *S1*, which allows a much finer mesh (0.4mm characteristic element size), while retaining reasonable calculation times. The centre of this model lies at a distance r_p=65mm from the cone centre. The BC's on the sheet edges of *S1* are obtained by linear interpolation of the displacements of the nodes in the corresponding region in the global model *G*. Interpolation of displacements of the drive-nodes (in space and time) is done in an automated way (ABAQUS sub-modelling technique), once the solution of the global model is available. In [3-4], the same FE strategy is used to assess the distribution of contact pressure under the SPIF forming tool, including an even higher mesh density in a 'small sub-model' *S2* (not considered here).

Both FE models use three layers of 1st order, reduced-integration brick elements for the sheet, while the forming tool is modelled as an analytical sphere that is rigid (i.e. it does not deform). The contact model is of the type 'hard node-to-surface contact', i.e. the surface nodes of the sheet are not allowed to penetrate the tool surface. Coulomb friction between tool and sheet is further assumed, i.e. the friction stress is proportional to the normal contact stress, with a proportionality (friction coefficient) denoted by f. The direction of the friction shear stress is determined by the (local) relative velocity between sheet and tool.

The calculation time of both these models is in the order of 2 days on a 16GB-RAM 2.4GHz CPU.

3.2 MATERIAL MODEL

As SPIF is a displacement-driven process, a logic choice to validate the FE model (comprising constitutive model and contact model), is the forming force, which can be experimentally measured (cf. the measurement method described in [4]). A good choice of material model (with a suitable parameter identification method) to obtain accurate forces in SPIF has shown to be very difficult [5-7]. In these papers, an inverse method is used to obtain the parameters of several hardening models with either a von Mises or a Hill yield locus. Identification is done on the same aluminium alloy (1.5mm thickness) with classical tests, i.e. a uniaxial tensile test, a simple shear test (in the sheet plane) and two Bauschinger tests, by opposite shearing in a shear tester with two different prestrains. In many cases, also an indent test (penetration of a SPIF forming tool into a clamped sheet, proposed in [5], is considered in the inverse method. While the identification for the classical tests can be done analytically (due to a homogeneous straining zone), the indent test requires an FE model for its identification. The advantage of including this test lies in the similarity to the SPIF process, and it appears to be required for accurate force prediction of SPIF [7]. A disadvantage is that a similar element type is required in the SPIF prediction as used in the indent test identification procedure, and parameter sets for either shell FE models (Lagamine software, developed at UCLiège) as well as brick models (i.e. *G* and *S1* models) are presented in [7].

It is concluded in [5-7] that the choice for an anisotropic Hill yield locus is no significant improvement compared to von Mises. Also, all material sets used in shell FE models and the global brick model *G*, result in severe forming force overprediction of a large wall angle cone of 60°. The best result for a 60° cone (cf. [7]), is for the large sub-model *S1* with a von Mises yield criterion in combination with the mixed isotropic-kinematic hardening law presented next.

The Cauchy stress $\boldsymbol{\sigma}$ is decomposed in a kinematic part $\mathbf{X}$, called the back-stress, and an isotropic part $\boldsymbol{\sigma}$-$\mathbf{X}$. The von Mises equivalent stress σ_{eq} of this latter part equals the size of the yield locus σ_F:

$$\sigma_{eq}(\boldsymbol{\sigma}-\mathbf{X}) \equiv \sqrt{\frac{3}{2}(\boldsymbol{\sigma}'-\mathbf{X}'):(\boldsymbol{\sigma}'-\mathbf{X}')} = \sigma_F \qquad (1)$$

in which the deviatoric part of a tensor $\boldsymbol{\alpha}$ is denoted $\boldsymbol{\alpha}$'. The evolution of the size of the yield locus σ_F is described by the saturating Voce law:

$$\sigma_F = \sigma_0 + K\left(1-\exp\left(-n\,\varepsilon_{eq}\right)\right) \qquad (2)$$

in which ε_{eq} is the von Mises equivalent strain, and σ_0, K and n are hardening parameters to be determined by the inverse method. The back-stress $\mathbf{X}$ follows the linear Ziegler evolution equation:

$$\overset{\triangledown}{\mathbf{X}} = C_A \frac{\boldsymbol{\sigma}-\mathbf{X}}{\sigma_F}\dot{\varepsilon}_{eq} \qquad (3)$$

in which $\overset{\triangledown}{\mathbf{X}}$ is the (objective) Jaumann time derivative of $\mathbf{X}$, $\dot{\varepsilon}_{eq}$ is the equivalent plastic strain rate, and C_A is a material parameter. The hardening parameters are given in Table 1.

In [7], it is seen that this law underpredicts the hardening under uniaxial tension, caused by fitting the model (with a limited number of parameters) to other tests in the identification procedure. As a result, it is also seen [7] that the forming force of a low wall angle cone (α=20°) is underpredicted with this material law in the large sub-model. Here, only a cone with a high wall angle (α=60°) is discussed. It should be noted that the strains reached in this cone are several times higher than those of the identification tests (classical tests and indent test).

Table 1: Hardening parameters, determined by inverse method for SPIF, from [7]

AA3103 (1.5mm)	
σ_0 (MPa)	20
K (MPa)	89
n	22.5
C_A (MPa)	83

4 FE MODEL VALIDATION

4.1 Validation of the material model

Figure 2 shows the force component along the Z-direction (Fz), and along the radial R-direction (Fr) from the FE large sub-model *S1* with this Mises-Voce-Ziegler law ('MVZ'). Two friction coefficients are considered, f=0 (frictionless) and the very high value of f=0.35. No tool rotation is imposed in these simulations. It is seen that friction hardly affects the simulation result. The measured force components are also given for the experiment without tool rotation, and a good agreement is obtained for both components. Also the experimental result with tool rotation is shown, which is also nearly identical. The whole Figure 2 thus validates the *material model* up to large strains. The FE contact model (including choice of f) is of minor relevance for these components, as are the exact friction conditions in the experiment.

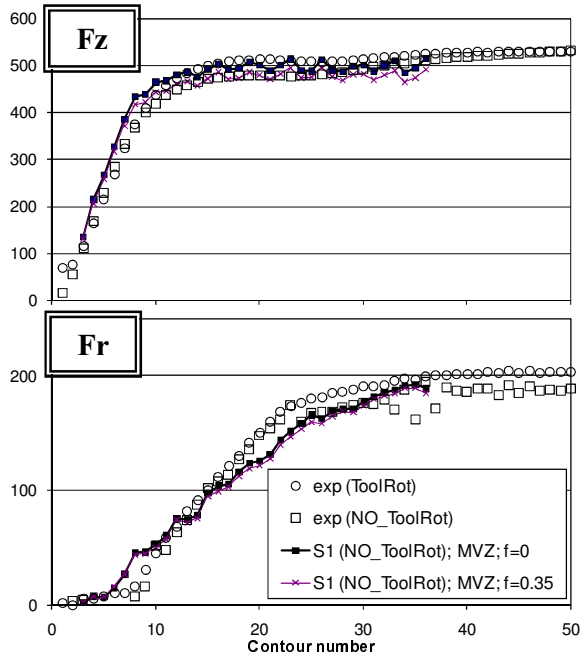


Figure 2: Predicted forming force components Fz and Fr (Unit: N) with different friction coefficients f, and comparison to the experimental components with and without imposed tool rotation

4.2 Validation of the FE contact model

Unlike Fz and Fr, a large relative difference is seen in the measured tangential force component Ft (along Θ, i.e. in the instantaneous tool movement direction) whether tool rotation is imposed or not. This is shown in Figure 3.

Also the FE simulation results depend highly on the friction coefficient used in the Coulomb friction law (cf. top graph of Figure 3; no imposed tool rotation). A nearly linear relationship is seen between the Coulomb friction coefficient and the magnitude of Ft. A coefficient of 0.09 (shown in the bottom graph) results in the best fit of Ft. As a final validation, tool rotation is also imposed in the FE model *S1* with this friction coefficient. It is seen that tool rotation indeed lowers Ft as it does experimentally, but not enough to exactly match the experiment. It is thus concluded that there is still some room for improvement of the FE contact model, which currently adopts the relatively simple Coulomb friction law.

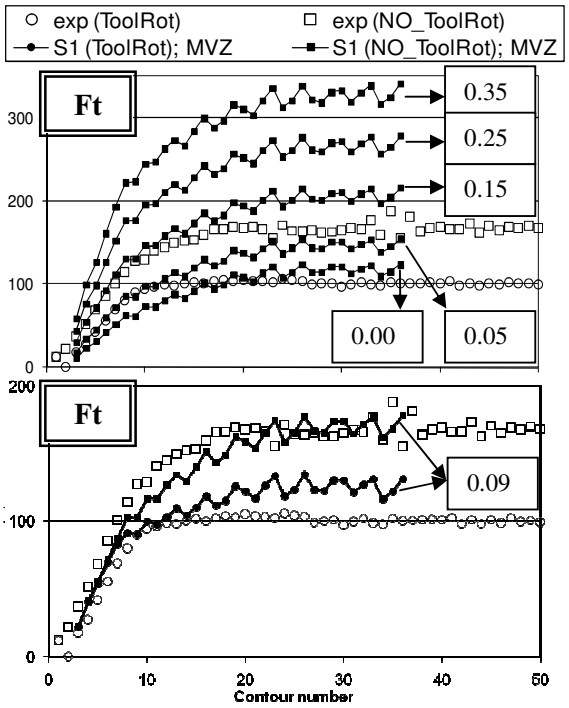


Figure 3: Experimental and predicted tangential forming force component Ft (unit: N) with and without imposed tool rotation. The boxes mention the adopted friction coefficient f in the FE model S1

5 PREDICTION OF THROUGH-THICKNESS SHEAR

Through-Thickness Shear (TTS) in the fully formed cone wall may be characterized by the shear angles in two perpendicular planes containing the sheet normal. The angle γ_{13} represents the shear in the cone wall direction, and γ_{23} in the local tool movement direction. In Table 2, it is seen that the FE model *G* underpredicts TTS. As a result, it overpredicts the forming force [7]. For the validated sub-model *S1* (friction coefficient of f=0.09), it is seen that tool rotation has a clear effect on TTS. Without tool rotation, the adopted value of the friction coefficient affects mainly the angle γ_{23}, i.e. the TTS along the local tool movement direction.

Table 2: Prediction of Through-Thickness Shear angles γ_{13} and γ_{23} (average in centre of sub-model S1) from FE models G and S1 adopting the Mises-Voce-Ziegler hardening law

FE model	ω_t (rev/s)	f	γ_{13}	γ_{23}
G	0.00	0.05	-2°	0°
S1	0.00	0.00	-7°	6°
		0.05	-7°	9°
		0.09	**-7°**	**11°**
		0.35	-5°	22°
	2.45	**0.09**	**-4°**	**7°**

6 CONCLUSIONS

This paper presents an accurate FE force prediction of an aluminium alloy, 60° wall angle SPIF cone, using a fine, brick element mesh and mixed hardening. Tool rotation is seen to affect the induced Through-Thickness Shear and the tangential force component in the FE model, the latter observation being experimentally confirmed.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) and the Interuniversity Attraction Poles Program from the Belgian State through the Belgian Science Policy agency, contract IAP6/24.

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