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The finite element implementation, validation and verification of a plane stress yield criterion for use in sheet metal forming analysis

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ABSTRACT

The Leacock 2006 orthotropic yield criterion, previously developed and experimentally verified by Leacock [1], was implemented as a rate independent, elastoplastic user material subroutine (UMAT) within the commercial finite element software PAM-STAMP 2G™. This paper focuses on the implementation and the computational and experimental validation of the Leacock UMAT. The UMAT architecture incorporates the Associated Flow Rule (AFR), and the Cutting Plane Algorithm for the integration of the elastoplastic constitutive equations. The UMAT driven simulations of deep drawing and stretching operations were compared to data collected from laboratory performed experimental deep drawing of AA2024-O and AA6451-T4, and stretching of AA2024-T3 under the action of a hemispherical punch. The Hill family of yield criteria provided a relative comparison. The Leacock 2006 UMAT provided an accurate prediction of the punch force versus displacement, and in the prediction of the experimental major and minor strain in the stretching of AA2024-T3. The Leacock 2006 UMAT provided an acceptable accuracy of the earing profile and the experimental punch force versus displacement during the deep drawing of the aluminium alloys 2024-O and 6451-T4.

1. Introduction

The use of the Finite Element (FE) method for the simulation of sheet metal forming operations is now a mature modelling methodology utilised across many industrial sectors. The non-linear FE modelling of the large deformation and rotations experienced during sheet metal forming processes is driven by an anisotropic material model, which is used to update the constitutive incremental stress and strain equations. The macroscopic, phenomenological plasticity theories within PAM-STAMP 2G™ have been extensively utilised for the explicit FE modelling of sheet metal forming processes [2]. The Leacock 2006 yield criterion requiring 7 calibration parameters from two types of experimental testing provides an accurate yield criterion with minimal calibration expense. Within this work, the capability of PAM-STAMP 2G™ can be further extended through the use of the user material subroutine (UMAT) functionality.

An accurate numerical description of orthotropic plasticity requires three components: a yield criterion for the accurate description of the anisotropic stress states at yield, a flow rule to relate the increment of plastic strain once the yield state has been exceeded, and a hardening law for a description of the strain hardening process undergone with continued plastic deformation. In addition, the numerical analysis is conditionally guided by the Kuhn–Tucker loading and unloading relationships and by the consistency condition.

The majority of the commercial software packages available, including PAM-STAMP 2G™, are based upon macroscopic, phenomenological plasticity theories. The yield criteria developed by Rodney Hill, the Hill family of yield criteria, are extensively utilised for the analysis of the orthotropic materials with the quadratic yield function proposed by Hill [3] commonplace [4,5,6].

The Hill quadratic (1948) yield criterion was a further development of the isotropic yield criterion proposed by von Mises [7] for anisotropic analysis through the introduction of orthotropic constants. Simple calibration is achieved through two tensile tests. However, the minimal calibration is countered by the questionable accuracy of the Hill 1948 yield criterion which is susceptible to first and second order anomalous behaviour observed in aluminium alloys [8]. There are two forms of anomalous behaviour often displayed by aluminium alloys: first order and second order. First order anomalous behaviour (often abbreviated to anomalous behaviour) occurs when the anisotropic yield locus is contained outside the von Mises yield locus when the r-value coefficient is

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less than unity, or vice versa, and is described as

$$r<1 \text{ when } \sigma_b>\sigma_y \quad \text{or} \quad r>1 \text{ when } \sigma_b<\sigma_y \tag{1}$$

where r is the r-value coefficient, equating to the r-value in the rolling or transverse orientation, σ_y is the yield stress in uniaxial tension, and σ_b is the yield stress in equibiaxial tension.

Second order anomalous behaviour (anomalous behaviour of the second order) was termed by Banabic et al. [9] to describe experimental behaviour commonly exhibited by aluminium alloys where the yield stresses and the r-values show opposite anisotropy trends in the rolling and transverse orientations. Second order anomalous behaviour is mathematically described as

$$r_0<r_{90} \text{ when } \sigma_0>\sigma_{90} \quad \text{or} \quad r_0>r_{90} \text{ when } \sigma_0<\sigma_{90} \tag{2}$$

Additionally the Portevin–Le Châtelier (PLC) effect negatively influences the Hill 1948 yield criterion when calibrated using the r-value (plastic strain ratio) method [10]. Subsequent yield criteria by Hill [11–13] were non-quadratic, incorporating the equibiaxial stress within the yield function. The Hill 1990 yield criterion addressed the previous inaccurate description of first order anomalous behaviour. However, an inability to describe second order anomalous behaviour was evident with the Hill 1990 yield criterion. Leacock [1] derived a stable form of the orthotropic plane stress yield criterion originally proposed by Hill [12] where the limitation of 'orthotropic sensitivity' as described by Hill [13] was completely removed. Aside from the Hill family of yield criteria, recent decades have witnessed the proposition of a plethora of non-quadratic yield criteria [14-22], each requiring significant calibration in terms of quantity and type of tests required.

The yield criteria proposed in the 21st century have primarily focused on accuracy, while neglecting the quantity and complexity of tests required for calibration as required by the Yld2004-18p [15] and Vegter yield criteria, respectively. An alternative approach was adopted by Leacock [1] focusing on providing an elegant solution for industry through the minimisation of the calibration tests required, while maximising accuracy to ensure industrial applicability. The yield criterion proposed by Leacock [1] was based on the Hill [12] yield criterion and offered an improved accuracy in principal stress space and in the planar orthotropic description of yield stresses and r-values for FCC, BCC and HCP metals [1]. The Leacock [1] yield criterion is insensitive to both first and second order anomalous behaviour, requiring the same quantity of test data used in the Hill 1990 yield criterion. Despite the obvious advantages, the Leacock 2006 yield criterion has yet to be implemented in a Finite Element Analysis.

The Associated Flow Rule (AFR), based on the Drucker [23] postulate of normality, has traditionally been used in the field of metal plasticity for the determination of the plastic strain increment from the yield locus. The Leacock (2006) yield criterion and

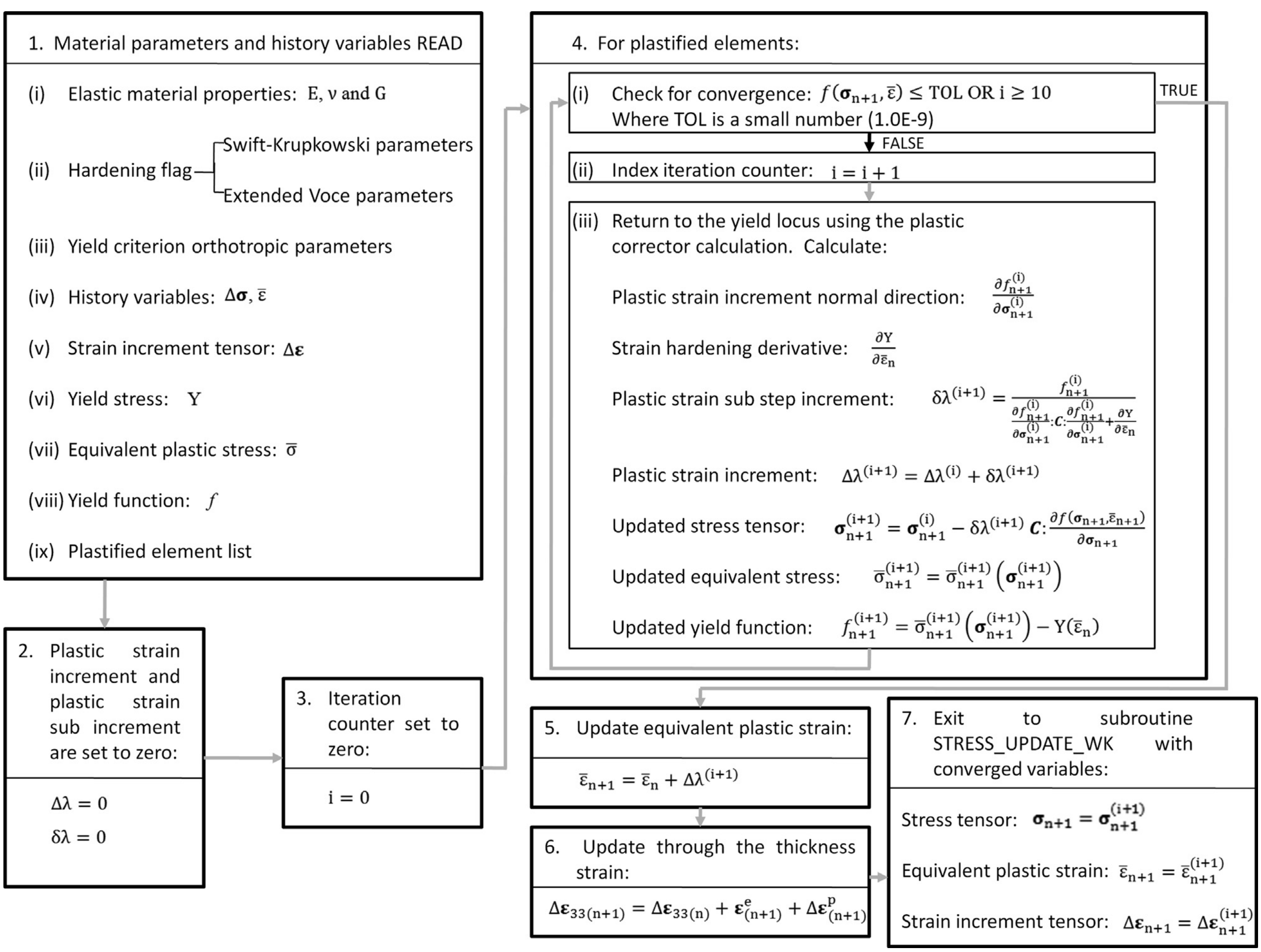

Fig. 1. A summary of algorithm employed within the plasticity subroutines for the solution of the plastic variables.