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NUMERICAL SIMULATION OF THE FORMING LIMIT CURVES OF A HEAT TREATED AA110-H14 ALUMINIUM ALLOY SHEET USING AN EFFICIENT IMPLEMENTATION OF A VPSC BASED MK MODEL

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The objective of this work is to numerically simulate the forming limit curves (FLCs) of a heat treated AA1100-H14 aluminum alloy cold-rolled sheet. To this end, a viscoplastic polycrystalline self-consistent (VPSC) model coupled with the well-known Marciniak and Kuczynski (MK) technique are used. Although the MK-VPSC approach has been successful in predicting realistic FLCs of different materials, the solution process of its classical implementation becomes computationally expensive and is not exempt from some complications of convergence near the failure stage. In order to avoid the resulting iterative procedure, an efficient algorithm is proposed and briefly described in this paper. Moreover, the numerical predictions obtained in this context are experimentally validated with measurements corresponding to hourglass-type (Nakazima) and bulge samples taken at 0°, 45° and 90° with respect to the sheet rolling direction.
As already mentioned, the VPSC formulation for modeling the aggregate behavior is implemented in this work in conjunction with the well-known MK approach. The MK analysis postulates the existence of a material imperfection such as a groove or a narrow band across the width of the sheet; see Fig.1. Typically, the initial imperfection factor $f=h^b/h$, i.e., the ratio of the thickness inside the band to that outside the band, is taken to be 0.99 – 0.999. The failure strains, ε_{11}^*-ε_{22}^*, are obtained after minimization of the curve ε_{11}^* versus the band inclination, such that the failure condition is reached when $\left|\bar{D}_{33}^b\right| > 20\left|\bar{D}_{33}\right|$ (**D** being the rate-of-deformation tensor). The MK equations are solved imposing small strain increments of the order of 0.003. To accurately capture the instant of necking, increments are usually reduced up to 100 times close to the failure condition. Equilibrium and compatibility conditions must be fulfilled at the interface with the band. Following the formulation developed by Wu et al. (1997) and implemented in Signorelli et al. (2009), the compatibility condition at the band interface is given in terms of the differences between the velocity gradient tensors $\bar{\mathbf{L}}$, $\bar{\mathbf{L}}^b$ inside and outside the band respectively:

$$\bar{\mathbf{L}}^b = \bar{\mathbf{L}} + \dot{\mathbf{c}} \otimes \mathbf{n} \qquad (1)$$

Vector $\dot{\mathbf{c}}$ can be obtained by solving the system of Eq. (1) together with the equilibrium condition and an incremental constitutive relation provided by the VPSC model. This results in a non-linear system of two equations (assuming that $\bar{L}_{23} = \bar{L}_{32} = \bar{L}_{13} = \bar{L}_{31} = \bar{L}_{21} = 0$ and $\bar{L}_{21} = 0$ or $\bar{\sigma}_{21} = 0$). This highly non-linear system of equations can be solved via a Newton-Raphson technique (Signorelli et al. 2009) that usually exhibits convergence drawbacks for strains levels close to the failure criteria. In order to avoid the iterative procedure, an improved algorithm is proposed: i) solve the mechanical state of the homogeneous zone in the reference frame; ii) express the solution of i) in the band reference frame [b]; iii) solve the boundary condition of the band zone in the groove reference frame [b]. In the reference frame [b], the band components of the velocity gradient and Cauchy stress tensors are complementary, i.e., if the velocity gradient component ${}_{[b]}\bar{L}^b_{ij}$ is known the corresponding stress component ${}_{[b]}\bar{\sigma}^b_{ij}$ is unknown:

$$
{}_{[b]}\mathbf{L}^{b}=\begin{bmatrix} \underline{L^b_{nn}} & L_{nt} & 0 \\ \underline{L_{tn}} & L_{tt} & 0 \\ 0 & 0 & \underline{L^b_{33}} \end{bmatrix}, \quad {}_{[b]}\boldsymbol{\sigma}^{b}=\begin{bmatrix} \frac{1}{f}\sigma_{nn} & \frac{1}{f}\sigma_{nt} & \underline{\sigma^b_{n3}} \\ & \underline{\sigma^b_{tt}} & \underline{\sigma^b_{t3}} \\ sym. & & 0 \end{bmatrix}, \tag{2}
$$

where the underlined components are determined with the VPSC model which provides the complementary state when a mix boundary condition is prescribed. In the absence of through thickness effects, the unknown values $\underline{\sigma^b_{n3}}$ and $\underline{\sigma^b_{t3}}$ should be ideally zero. This simple procedure allows obtaining an efficient and robust prediction resolution of MK prediction of localized necking of sheet metal forming.

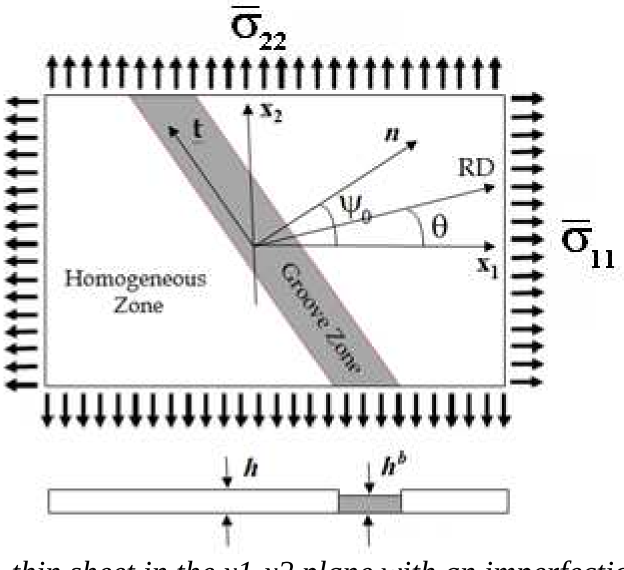

Fig.1: A thin sheet in the x1-x2 plane with an imperfection band.

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