

Full length article

New biaxial yield function for aluminum alloys based on plastic work and work-hardening analyses

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ABSTRACT

Yield locus measurements and their analytical descriptions has been the bases for modeling metal processing. These analytical descriptions play a role in models to predict limit strains observed during determination of forming limit diagrams of flat metal stock as means to evaluate their fabrication performance. Some of these analytical descriptions use the isotropic or anisotropic plastic potentials that take into account the crystallographic texture of the material. The applicability of such potentials is validated by comparing their predictions to that of unidirectional tensile data. In the current work, this approach is reversed to examine whether the constitutive relations, which replicate the measured stress-strain diagrams, can generate a two-dimensional section of the yield locus. The strategy is to sum the computed plastic work (PW) from unidirectional mechanical tests in two principal directions which also accommodates the biaxial interaction strains. The resulting yield function includes f^0 and f^9 , the prescribed stress ratios and the texture parameters R^0 and R^9 in their respective principal directions. The prescribed PW at an arbitrary strain during unidirectional tensile test is equated to the work sum from the biaxial stresses on the premise that the plastic flow-stress registers only the increasing density of obstacles it generates. The computed biaxial yield stresses showed good fits for AA5154 and AA5754 with only small modification due to latent work hardening.

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1. Introduction

Formability of metallic sheet for stamping and deep-drawing operations has been of high industrial interest in order to optimize die-designs for fabrication processes and the progress of such studies to 1977 has been compiled by Hecker et al. [1]. The practical test of examining etched patterns on sheet surface to determine the principal strains at which limit strains of localized necking occur has been developed by Keeler [2] and Goodwin [3]. This mapping of limit strains for sheet fabrication has become the industrial standard, referred to as the forming limit diagram (FLD). The theoretical basis for the analysis is based on the observation that plastic shape-change is independent of hydrostatic stresses whereby the principal stresses are all equal. A very simple yield locus is the well-known von Mises criterion for the occurrence of plastic flow. Today's experts in plasticity theory know that it merely represents a

hypersphere in stress deviator space, i.e. it is the simplest possible closed surface in that sphere. Reid [4] points out that it can be based on the notion that plastic flow begins when the elastic distortion energy reaches a critical limit, usually designated at 0.2% off-set strain. However, from a physical point of view, this criterion is only meaningful for a material which has ideal isotropic elastic properties such as tungsten but not for the other crystalline materials. Nevertheless, in materials engineering the von Mises approximation is often used for cubic materials with a weak crystallographic texture as a reasonable first estimate. This analytical basis for a yield locus was accompanied by experimental observations that the incremental component of in-elastic strain may be computed by differentiating the yield function, in terms of stresses, with that specific stress component. This initial Levy-Mises criterion [4] has become known as the associated flow rule whereby the total plastic strain increment is normal to the yield surface. This extension of the von Mises criterion based on the existence of a critical magnitude of distortion energy for initiation of plastic flow to pre-strained work-hardened structure, as conventionally perceived, inherently assumes that the measured plastic work

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directly corresponds to the elastic distortion energy and that elastic anisotropy can be ignored (reasonable for tungsten, not unreasonable for aluminum, as the elastic anisotropy of aluminum single crystals is not very large). The current work suggests that plastic work initially follows a quadratic stress relation which becomes cubic and returns to quadratic at very large strains and inversely correlates with the work-hardening coefficient as will be examined in the discussion section. The seminal advance in the application of mathematical theory of plasticity to sheet formability was initiated by Marciniak and Kuczynski [5] in order to predict localized necking in biaxial stretch cases. However in order to initiate this strain localization, an initial existing groove in the plane of the sheet was envisioned. At present, this analysis is widely invoked to introduce the role of texture in FLD [6] and recent hypotheses invoke yield functions which do not retain the quadratic stress relation and hence the concept of distortion energy is relaxed. Overviews of such works are found in the following reports [7,8].

The validation of yield function is experimentally difficult since for cases other than unidirectional tests, the determination of the flow stress components and its accompanying plastic strains are imprecise. One well-defined test is that of stretching thin-walled tubular specimens with correlated internal pressure. The difficulty of precise strain measurement has been overcome by Kuwabara's group [9] using a spherometer, a specially developed displacement device for large in-elastic strains. In their study the stresses along loading paths of set biaxial ratios parallel to the cylinder axis (ϕ) and its circumference (θ) were determined and the total energy (TW) required for specific deformation modes were equated to the area defined by the stress-strain diagram for unidirectional tension to attain a given tensile strain to define the evolution of yield loci. Using extruded tubing of AA5154, the yield loci data at increasing degree of cold work were compared to various theoretical yield functions mentioned above [7,8]. Another notable study is due to Iadicola et al. [10] which measured the in-plane stresses of biaxial stressed sheets of AA5754 using in-situ X-ray diffraction. From the quasi-static recording during unidirectional tests (UD), balanced biaxial (BB) and plane-strain (PS) cases, the principal stresses and strains were reported. These short-hand notations have been retained in this work for the ease of cross-referencing.

The strategy to derive constitutive relations for in-plane biaxial-stressed sheet in this work is to reverse that of conventional practice of yield function determination in which the fit parameters are matched with measured in-plane stresses at points of constant total work. The constitutive relation derived from this yield function is compared to the unidirectional tensile one to attest to its validity. In the current work, constitutive relation analyses (CRA) which can replicate the measured stress-strain diagram using at least two-fit loci become the starting point from which the plastic work due to biaxial stresses are calculated. The CRA procedure defines a new yield stress (σ_0^{final}) by back-extrapolating the plastic response from beyond the yield phenomenon and the associated yield point elongation (YPE). This determination corresponds to an off-set strain of 0.02%, slightly above the proportional limit as described elsewhere [11]. Hence the plastic work (PW) is defined as $\int (\sigma - \sigma_0^{\text{final}}) d\epsilon_p$ wherein σ is the applied stress, $(\sigma - \sigma_0^{\text{final}})$, the flow stress and ϵ_p , the logarithmic (true) plastic strain. Note that the total work (TW) includes $\int \sigma_0^{\text{final}} d\epsilon_p$ which give rise to heat as in the case of friction stress and contributions from the yield phenomenon are removed. Since the new constitutive relations by Saimoto and Van Houtte (S-VH) [11] based on the Taylor slip model directly correlate the flow shear stress to the shear strain [11,12], conversion to normal stress and strain was performed in order to use the width to thickness strain ratio R (Lankford ratio), as an indirect measure of textural effects on plastic flow. The hypothesis invokes that under

biaxial stress-states the incurred principal plastic strains are additive and also plastic work (PW) under proportional loading are additive. The net result for sheet stock is that the derivative of PW at a given thickness strain gives rise to the effective compression stress at that point. This slope-method offers the possibility of comparing the yield locus at constant PW to that of constant thickness strain. However the usual procedure is to use constant TW for the cases reported [9,10] which includes the yield stress and explicitly described by Barlat et al. [13,14]. Comparison of this criterion of constant TW to that of constant PW will be presented. Hence the new biaxial yield function is based on this PW relation that can be analytically derived using the constitutive relation which replicates the stress-strain diagram and integrated with respect to the in-plane stresses which are proportionally related. By equating PW from tensile tests at a given strain and using this relation, the biaxial stresses and strain can be calculated.

The attribute of analytical prediction of yield locus from constitutive relations is two-fold.

- 1) The yield locus can be continuously mapped and compared with the data to assess the degree of fit. Moreover the effect of the texture-parameter R on the point-by-point curvature or tangent at any given stress ratio can be assessed.
- 2) From the calculated in-plane stresses for any given stress ratio, the strains corresponding to those stresses can also be calculated from which the principal major (minor) stress-principal major (minor) strain loci can be generated. This procedure also implies that CRA of such measured loci for the in-plane stresses can be analyzed to predict the strains in three principal directions. For example, such analysis for PS case can be used to ascertain if the actual test met the condition of continuous zero strain in the minor axis. The evolution of stresses under PS or BB conditions can be CRA analyzed to assess ductile failure and FLD prediction according to prior-described methodology [15].

2. Analytical procedures

2.1. Derivation of yield function based on plastic work

Fig. 1 shows CRA of UD test in ϕ direction whereby the two-fit

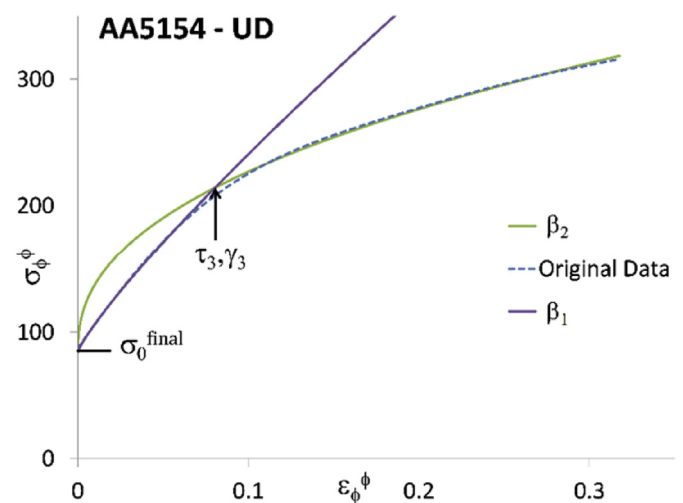


Fig. 1. Stress-strain diagram for AA5154 for UD ϕ axis from Kuwabara et al. [9] showing the two-fitted loci using CRA. Note the definition of σ_0^{final} and the location of corresponding coordinates to τ_3 and γ_3 which is slightly off-line giving rise to transition region in derived expended-energy plots.

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