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Implementation and application of a temperature-dependent Chaboche model

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ABSTRACT

The literature shows that shear fracture of advanced high strength steels (AHSS) is affected by strain hardening at large strain, as well as the temperature dependence of flow stress and strain hardening. The role of non-isotropic hardening, such as would be expected to be important in reverse strain paths as encountered during draw-bend testing or drawing sheet metal into forming dies, has been difficult to assess without a practical constitutive model combining temperature-dependence *and* non-isotropic hardening capabilities. Such a model has been developed and implemented in Abaqus Standard via the UMAT subroutine. In order to apply and test the constitutive implementation, the material model was fit using alternate parameter-identification procedures starting from compression-tension (CT) data: 1) fit directly from reverse-path, CT data, and 2) fit indirectly, by combining the direct CT data plus extrapolated data at larger strains where the extrapolation uses verified large-strain monotonic hardening character. The resulting material models were used to simulate draw-bend fracture (DBF) tests for six AHSS. The results show that the indirect method improves the predictions of shear fracture significantly, allowing accurate predictions. It was also shown that the influence of non-isotropic hardening aspects are not critical to accurate predictions as long as the high-strain strain hardening is reproduced accurately. These results suggest a practical and effective method for extending measured tensile hardening to otherwise unattainable strains based on the constant ratio (α in the H/V model) of power-law and saturation-stress strain hardening at a given temperature. The success of this approach suggests that α is a material constant (describing the fundamental strain-hardening character) that depends on temperature but is unaffected by the details of transient hardening following abrupt path changes. Furthermore, the essentially transient nature of hardening following path changes is supported.

1. Introduction

Advanced high strength steels (AHSS) are increasingly being used in automotive body and structural parts because they offer opportunities for reducing vehicle weight while improving safety performance (Kuziak et al., 2008). However,

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springback and bending-affected formability remain significant impediments to their adoption (Walp et al., 2006; Chen et al., 2008; Wagoner et al., 2009a, 2009b). *Shear fracture* is a bending-dominated failure mode that has proven difficult to predict using standard industrial finite element procedures, testing methods, and forming limit diagrams (FLD) (Sriram et al., 2003; Stoughton et al., 2006; Huang et al., 2008; Sung et al., 2012).

Shear fractures were initially reported to occur with little or no obvious thinning near the fracture (Wagoner, 2006).[1] While fracture with no local thinning implies brittle behavior, the recent scientific literature, as outlined below, finds little support for that initial observation.

Shear fracture is reproduced in the laboratory by reproducing the characteristic drawing, stretching, and bending over a tight radius. Several experimental techniques have been used to accomplish this (Damborg et al., 1997, 1998; Damborg, 1998; Hudgins et al., 2010; Walp et al., 2006; Luo and Wierzbicki, 2010). More recently, a specialized technique using controlled displacement rates on both sides of the bending region was introduced. Called the draw-bend fracture ("DBF") test, it has been applied to shear fracture of AHSS (Wagoner et al., 2009a, 2009b; Kim et al., 2011; Sung et al., 2012). Such techniques have been shown to produce fracture at the maximum draw load (Yoshida et al., 2005; Hudgins et al., 2010), within 1 mm of additional draw distance (Kim et al., 2011).

Using DBF tests, the roles of temperature on hardening (Kim et al., 2011; Sung et al., 2012) and the strain hardening at large strains (Lee et al., 2013) were shown to be dominant material factors affecting shear fracture, formability, as well as the process variable friction coefficient (Kim et al., 2014). Because the maximum strain rate is approximately 10/s in industrial sheet metal forming operations (Sung et al., 2012), deformation-induced heating for AHSS leads to a significant temperature rise, 100–120 °C, in the bending region, thus promoting strain localization there (Kim et al., 2011; Sung et al., 2012).

A new combined Hollomon (1945) and Voce (1948) constitutive form for temperature-dependent strain hardening, or "H/V model", was shown to reproduce the large-strain hardening behavior and the temperature sensitivity of many AHSS (Sung et al., 2009, 2010). Recently, H/V models were shown to predict strain hardening accurately at strains up to 6 times larger than tensile measurements (Smith et al., 2014). When applied to shear fracture via DBF test simulations, the formability was predicted much more accurately than with standard isothermal constitutive models based on Hollomon or Voce forms (Kim et al., 2011).

In spite of the proven accuracy of H/V laws, H/V-based simulations of the DBF test still over-predicted the formability of AHSS in many cases, although such comparisons were much improved over isothermal simulations, with average errors of 2–8% vs. 26–48%, respectively (Kim et al., 2011).

One obvious possibility for the remaining source of the discrepancy between simulated and measured DBF formability lies with the reverse-path hardening behavior of AHSS, which differs significantly from isotropic hardening for AHSS (Sun, 2011; Piao et al., 2012a; Sun and Wagoner, 2013). The reduction of flow stress after strain reversals would be expected to promote early localization and fracture by reducing the maximum draw stress and thus causing early instability. Such stress reversals are present for many elements of material that are drawn over the die radius. Unfortunately, it is not a simple matter to test the role of non-isotropic hardening (i.e. reproducing the reverse-path results) for DBF applications because of the known importance of small temperature excursions (typically up to 120 °C) that occur because of deformation-induced heating at typical industrial strain rates. Thus, a temperature-dependent version of non-isotropic hardening is required.

AHSS typically exhibit strong effects of stress reversals, including three characteristics: the Bauschinger effect (i.e. reduced yield strength compared with previous flow stress), transient behavior immediately after re-yielding (rapid strain hardening, typically for strains of ~0.03 after the path reversal), and long-term or "permanent" softening (sometimes seen over the entire strain range available from experiments, but always diminishing at larger strains) (Geng, 2000; Geng and Wagoner, 2002; Sun, 2011; Sun and Wagoner, 2013). The third of these, if present, was expected to be most important for shear fracture, because shear fracture is sensitive to flow stress and hardening at strains of approximately 0.5 (Lee et al., 2013; Luo and Wierzbicki, 2010). In addition, some steels show "overshoot", whereby the flow stress temporarily exceeds the expected isotropic-hardening flow stress. This effect is not considered in the current work.

Various plastic hardening models have been proposed to reproduce the three reverse hardening characteristics outlined above (Geng and Wagoner, 2002; Chun et al., 2002a, 2002b; Yoshida and Uemori, 2002, 2003; Chung et al., 2005; Lee et al., 2007; Sun, 2011; Sun and Wagoner, 2013). The role of constitutive complexities in the accuracy of springback simulations has been reviewed (Wagoner, 2004; Wagoner et al., 2006, 2013). The standard Chaboche model implemented with multiple nonlinear back-stress components can adequately describe the first two effects, i.e. Bauschinger effect and the transient behavior with a saturation towards the monotonic hardening curve (Chaboche, 1986, 1989; Ohno and Wang, 1993; Abdel-Karim and Ohno, 2000). However, a linear term can also be added to a standard Chaboche model in order to reproduce the permanent softening (Chung et al., 2005; Lee et al., 2007; Sun, 2011; Sun and Wagoner, 2013). In particular, Sun and Wagoner (2011, 2013) showed that the reverse-path hardening of AHSS can be reproduced accurately utilizing a modified Chaboche-type model with 2 nonlinear terms and 1 linear term.

In principle, the challenge for testing the hypothesis that non-isotropic hardening is needed for predicting shear fracture is to apply an accurate temperature-dependent isotropic hardening model in conjunction with a treatment of non-isotropic hardening. Such formulations have been presented (Chaboche, 1986, 2008; Ohno et al., 1989; McDowell, 1992; Mücke and

[1] For those interested in seeing practical examples of shear fracture, including photos of fractured automotive parts, the (Wagoner, 2006) reference may be consulted.