

A Combined Isotropic, Kinematic and Cross Hardening Model for Magnesium AZ31B-H24 under Non-linear Strain Loading Path

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Abstract. A fully modularized framework was established to combine isotropic, kinematic, and cross hardening behaviors under non-monotonic loading conditions. Three sets of state variables were defined and applied to consider the effects of, a) loading history, b) twinning and de-twinning and c) different pre-strain. Experiments under two types of non-proportional loading conditions were conducted along different orientations, 1) uniaxial compression-tension reversal loading with different amounts of compressive strains, and 2) two-step uniaxial tension, known as cross-loading conditions, with different pre-strains. No apparent cross-hardening effect was observed for this material. The calibrated new hardening model, with an anisotropic CPB06ex2 yield criterion and an eMMC anisotropic fracture model, has been implemented into Abaqus/Explicit as a user material subroutine (VUMAT). Good correlation was observed between experimental and simulation results.

1. Introduction

Magnesium alloys have been considered as a representative material of lightweight design in the automotive industry to reduce energy consumption and greenhouse gas emission. The de-twinning phenomenon occurs under compression-tension reversal loading when the subsequent tensile load is performed along the c-axis of the twinned areas, generating an unusual concave shape in the tensile stress-strain curve (Brown, Agnew et al. 2005, Lou, Li et al. 2007, Piao, Chung et al. 2012). The objectives of this paper are to, a) develop a constitutive model for magnesium alloy sheets, covering both monotonic and non-proportional loading conditions, b) conduct a sufficient set of experiments under non-linear strain path, including both reversal and cross-loading condition, and c) implement both the constitutive model and fracture model into finite element analysis to predict the non-linear historical fracture behavior.

2. Constitutive Modeling

Very strong anisotropic effects have been observed in this material, magnesium AZ31B-H24. The CPB06ex2 anisotropic yield criterion was calibrated for magnesium AZ31B-H24, which could concurrently fulfill a) different material strengths and plastic flows along different orientations, and b) the asymmetric yield strength between tension and compression, based on the work from Plunkett, Cazacu et al. (2008), Jia and Bai (2015). The modified semi-analytical Sachs model (Jia and Bai 2015) can be extended to incorporate the kinematic hardening behavior, using the state variables. Therefore, an additional item is defined, as follows

$$\bar{\sigma}_K = \text{sign}(\dot{\mu}) \left[(A_{K1}\mu - A_{K2}\varepsilon_C)(\bar{\varepsilon}^p + \varepsilon_0 - \varepsilon_C)^n + X_K \sqrt{\alpha^{dev} : \alpha^{dev}} \right],$$

where

μ is the *ad-hoc* de-twinning state variable, evolves from 1 (no de-twinning) to 0 (de-twinning

finished). ε_C is the compressive strain in previous loading history. A_{K1} and A_{K2} are material coefficients. X_K is the loading history state variable identifying the transition area, reads,

$$X_K = \frac{1 - \frac{\sigma : \alpha}{\|\sigma\| \|\alpha\|}}{2},$$

α^{dev} is the deviatoric part of the “dummy” back stress. The modified model becomes,

$$\bar{\sigma}_{NewSachs} = A_1(1 - \chi)X_T + [A_2\chi X_T + A_3(1 - X_T)](\bar{\varepsilon}^p + \varepsilon_0 - h\varepsilon_B)^n,$$

where χ indicates the fraction of the to-be-twinned grains that have already twinned, ranges from 0 to 1. It is defined as follows,

$$\chi = 1 - \exp\left[-4\left(\frac{\bar{\varepsilon}^p - h\varepsilon_B}{\varepsilon_1}\right)^a\right].$$

X_T is the fraction of grains expected to be twinned. ε_B is the historical accumulated plastic strain from the previous loading transitions, excluding the de-twinning process. h is an additional material coefficient attached to ε_B to control the isotropic hardening. A_1 , A_2 , and A_3 are simplified material coefficients. The kinematic hardening behavior during cross loading can be further compensated by an additional item $\bar{\sigma}_C$, defined as

$$\bar{\sigma}_C = -X_C^\lambda \sqrt{\alpha^{dev} : \alpha^{dev}},$$

Here, X_C is the key state variable governing the smoothness in transition during cross loading,

$$X_C = 1 - \left| \frac{\sigma : \alpha}{\|\sigma\| \|\alpha\|} \right|.$$

λ is an exponential material coefficient. Conclusively, the final constitutive model for magnesium AZ31B-H24 becomes

$$\bar{\sigma} = (\bar{\sigma}_{NewSachs} + \bar{\sigma}_K + \bar{\sigma}_C)f_{ext}(\eta, \bar{\theta}),$$

Strong anisotropic fracture has been observed in magnesium AZ31B-H24. An eMMC fracture model is applied for this material with linear transformed anisotropic equivalent plastic strain, based on the work from Jia and Bai (2015). In this paper, an additional assumption is made to incorporate the twinning/de-twinning effect as follows. The damage accumulation is temporarily deactivated, between the initialization and 90% completion of de-twinning.

3. Experimental Results and Numerical Simulation

The proposed constitutive model with CPB06ex2 anisotropic yield criterion and eMMC fracture model has been implemented into Abaqus/Explicit as a user material subroutine (VUMAT). The thickness for reversal loading test specimen was set as 2mm while the one for two-step tension was set as 1mm. Three different orientations, 0°, 45°, and 90° were assigned for both models. The simulated results were then compared to the experimental ones, which were all from DIC. One can see that the new hardening model is capable to predict the compression-tension kinematic hardening behavior with pre-strain effect. The eMMC model with associated de-twinning effect could predict the fracture strains very well under 10% nominal pre-strain. The comparison of true stress-strain between experimental and simulated two-step uniaxial tension is illustrated in Figure 2, with pre-strains under different amounts and orientations. One can see that the second step true stress-strain curves with the same orientation are similar under different pre-strains. No additional hardening is apparently observed at the beginning of the second step uniaxial tension, when the loading orientation changes. In conclusion, no clear cross-hardening effect is observed for magnesium AZ31B-H24 alloy sheet in the current experimental result. The hardening curves under all scenarios are well correlated with experimental results.

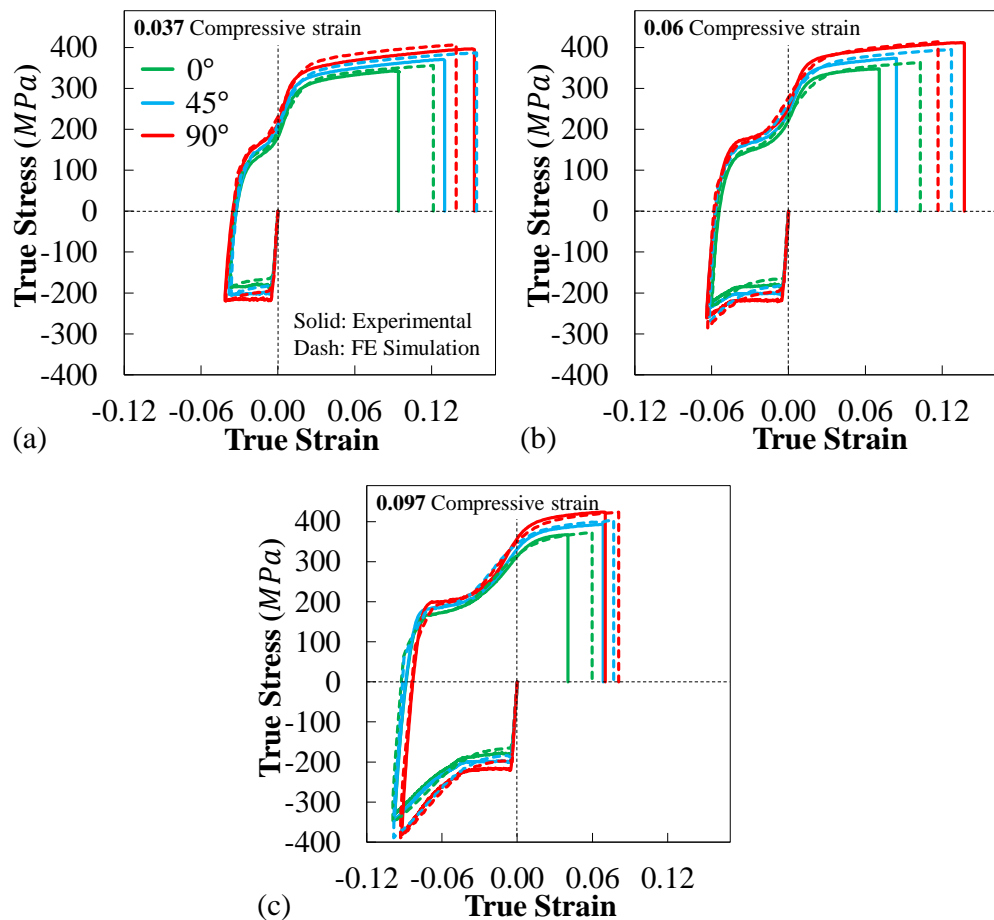


Figure 1 Comparison between tested and simulated true stress-strain curves of 2mm thickness AZ31B-H24 sheets up to fracture along 0°, 45° and 90° orientations, under compression-tension reversal loading with a pre-compressive strain of a) 0.037, b) 0.06, and c) 0.097.

4. Conclusions

A new Sachs-based constitutive model was developed for magnesium AZ31B-H24 alloy sheet, with a fully decoupled framework to combine isotropic, kinematic, and cross hardening behaviors. In order to verify the new constitutive model, two different types of non-proportional loading tests were conducted along different orientations, a) uniaxial compression-tension reversal loading with different pre-compressive strains, and b) two-step uniaxial tension, known as cross-loading conditions, with different pre-strains. No apparent cross-hardening effect was observed in the two-step uniaxial tension experimental results. The new model was sequentially calibrated by the experimental results from a set of different monotonic loading conditions, and a), b) above, with non-aftereffect. The calibrated new constitutive model, an anisotropic yield criterion CPB06ex2, and an eMMC anisotropic fracture model have been implemented into FE analysis to reproduce the non-proportional experiments through a user material subroutine (VUMAT) in Abaqus/Explicit. Good correlation was observed between experimental and simulation results, in both material strength and fracture behavior.

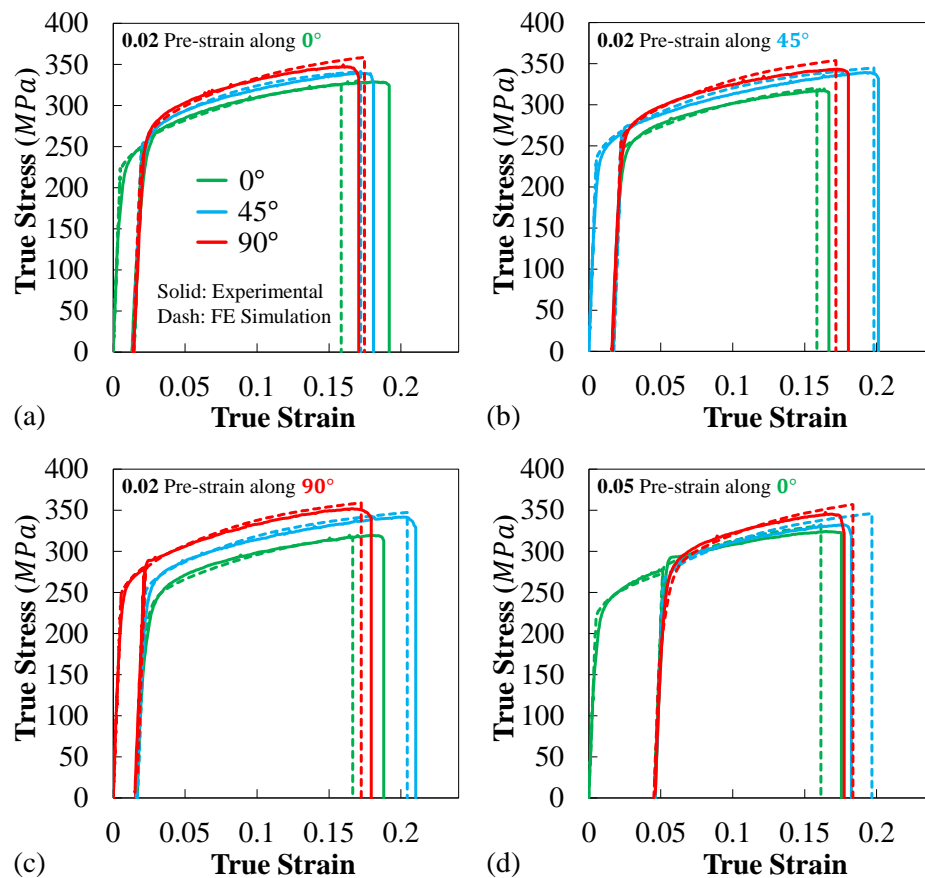


Figure 2 Comparison between tested and simulated true stress-strain curves of 1mm thickness AZ31B-H24 sheets up to fracture, under two-step uniaxial tension with a pre-strain of a), b) c) 0.02, d) 0.05, along a orientation of a), d), 0°, b), 45°, and c), 90°.

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