An elasto-plastic constitutive model of magnesium alloy sheet at warm forming temperature under strain path changes

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Abstract. In the current work, a continuum-based approach is discussed in order to describe the plastic hardening behavior of magnesium alloy sheets under strain path changes at warm forming temperature. The constitutive model is represented to use an anisotropic distortional yield function combining a stable component and a fluctuating component. The stable component includes the yield function that represents the material’s anisotropy or the strength effect between tension and compression. The evolution of the fluctuating component is reformulated based on recently developed HCP metal’s distortional hardening model at room temperature. The modified models were implemented into finite element (FE) software via user-material subroutine. Predicted stress-strain curves of tension-compression-tension (TCT) and compression-tension-compression (CTC) loadings for two pre-strains were compared with experimental results. Overall, the proposed model could give reliable agreement with experimental data.

1. Introduction
Magnesium alloy sheets exhibit unique mechanical behaviors against other cubic-structured crystals: 1) asymmetry in yield strength, and 2) asymmetry in hardening. The first has been observed in the monotonic tension and compression tests where the yield stress in tension is usually larger than that of compression [1].

Due to strong basal texture of magnesium alloy sheets, the second phenomenon could be measured under in-plane compression or compression followed by tension, in which stress-strain curves showed concave-up or S-shaped hardening curves. The activation of twinning or annihilation of twins (untwining) have been regarded as the main reason of the unique flow stress response in the magnesium alloy sheets [2,3]. Moreover, the aforementioned unique mechanical behaviors have not been shown when the magnesium alloy sheet was heated.

In the present study, a continuum-based constitutive model for the magnesium alloy sheet is developed to capture the asymmetry in yield strength and anisotropic hardening in stress-strain curves under various loading conditions. Moreover, the proposed model is extended to describe the mechanical behavior at the warm temperature. For the anisotropic hardening, a distortional hardening approach for symmetric model has been modified [4–6]. For the yield stress differential, the yield surface CPB 2006 model is employed under plane stress conditions [7]. As for the validation purpose, the stress-strain responses to the load reversals are reproduced by the proposed models.
2. Experimental procedure
AZ31B magnesium alloy sheets produced by POSCO were used for the study. Tension/compression tests at room temperature were conducted. Standard tensile specimens based on ASTM-E8 for uniaxial tension were machined to the rolling direction.

The width and thickness of the gage region was 6 mm and 1.4 mm, respectively, and the gauge length was 25 mm. Uniaxial tensile tests were conducted using a universal testing machine with strain rate of $10^{-3}$/s. Uniaxial compression and compression followed by tension were also performed using a special cyclic test machine (Fig. 1).

A hydraulic system was used to apply normal force for preventing the buckling of specimen during compression [8].

![Figure 1. Experimental testing machine](image)

3. Results
The developed constitutive models based on the distortional hardening law and asymmetric yield surface were implemented into the finite element (FE) software ABAQUS/Standard 6.12 by the user-material subroutine (UMAT). For the FE modelling for various loading conditions, a four-node shell element with reduced integration point, S4R, was used.

![Figure 2. Stress-strain curves for (a) uniaxial tension, (b) uniaxial compression](image)
Figure 3. Predicted results of uniaxial tension at warm temperature

Experimentally measured stress-strain curves for tension and compression are shown in Figure 2. The fitted curves are also provided. Significant asymmetry in yield strength and hardening curves are obvious from the monotonic tensile and compressive tests. Figure 4 describes the comparison between experimental and simulated results under uniaxial tension at warm temperature.

Figure 4 shows the comparisons of the measured uniaxial tension-compression-tension (TCT) and compression-tension-compression (CTC) tests with those conducted by the FE simulations. Two different pre-strains are subjected; 2% and 4%. Overall, the developed constitutive models can reproduce the main characteristics of experimental results under loading path changes. The S-shaped hardening behaviors during compression followed by the tension and the concave-up shape of flow curves during compression are well described.
Figure 4. Comparison between experimental and simulated results for CTC/ TCT conditions

4. Conclusion
The continuum based constitutive modeling was proposed to capture the unique anisotropic and asymmetric hardening behavior of magnesium alloy sheets under strain path changes. The modeling procedure included the re-formulations of asymmetric initial yield surface and distortional anisotropic hardening law. The first reproduced the yield strength differential in tension and compression, and the latter could describe the sigmoidal flow stress evolution under strain path changes.

Predicted stress-strain curves of tension-compression-tension (TCT) and compression-tension-compression (CTC) loadings for two pre-strains were compared with experimental results. Overall, the proposed model could give reliable agreement with experimental data.

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