Warm Forming Simulation of a ZEK100 Magnesium Door Panel

Kaab Omer¹, Clifford Butcher¹, Michael Worswick¹ and Tim Skszek²

¹University of Waterloo, 200 University Ave W, Waterloo ON, Canada, N2L 3G1
²Magna International, Inc. 750 Tower Drive, Troy MI, USA, 48098

*komer@uwaterloo.ca

Abstract. The warm forming of a door panel made of commercial grade ZEK100 magnesium alloy sheet was modelled using finite element techniques (Autoform). The operation consisted of a heating step, a forming step and a cooling/springback step. The material properties of the ZEK100 blank were modelled using a set of temperature- and strain rate-dependent stress-strain curves, which were derived based on a Zerilli-Armstrong constitutive model. In order to simplify the material model to enable its complex response to be represented within a commercial finite element code, the anisotropy of the magnesium sheet was approximated using a Banabic-2005 yield surface and yield asymmetry was neglected, a reasonable approach for warm forming. Necking was predicted using a set of forming limit curves obtained at different isothermal temperatures. The entire forming model was run at a punch speed of 160 mm/s, and two initial blank temperatures: 215 and 230 °C. The tooling was initially at room temperature. The model predicted that the blank cracked when its initial temperature was 215 °C due to excessive cooling. The best formability (lack of wrinkling and necking) was predicted when the blank was heated to 230 °C. These predictions agree well with the forming trial outcomes.

1. Introduction

Most automotive structural components are made of either steel or aluminum alloys. Magnesium alloys such as ZEK100 are also considered due largely to their low density and high weight reduction potential. There are, however, several challenges associated with the forming of magnesium sheet. These alloys exhibit limited formability at room temperature, although rare earth-alloyed magnesium sheet, such as ZEK100, generally exhibit higher formability than AZ31B [1]. At elevated temperatures, the formability of magnesium alloys does improve considerably [1,2]. Aside from formability issues, capturing the constitutive properties of magnesium alloys also poses several challenges. Magnesium alloys exhibit tension-compression asymmetry and strong transverse and in-plane anisotropy [3,4]. Recent studies have addressed characterization of the constitutive behavior of magnesium sheet alloys, such as AZ31B and ZEK100, however, implementation of numerically efficient constitutive models within commercial finite element codes used by industry to simulate stamping operations requires further advancement.

Recently, constitutive models have been devised to address the unique challenged posed by ZEK100 [3–5]. These models attempt to address the strong anisotropy and tension-compression asymmetry, as well as the rate- and temperature-dependent properties, all of which affect formability. In addition, Omer et al. [6] have characterized the heat transfer coefficient (HTC) of ZEK100 on steel dies, as a function...
of contact pressure, since the HTC represents a key boundary condition when forming pre-heated sheet using room temperature tooling.

The current work considers the implementation of an approximate constitutive model to simulate the warm forming of large-scale ZEK100 parts using a commercial code, Autoform, commonly used within the sheet forming industry. This implementation utilizes the existing constitutive model due to Kurukuri et al. [7], as well as the recent HTC characterization results by Omer et al. [6]. A finite element (FE) model is developed of the warm forming of a door inner panel made of ZEK100 [8]. The results of the FE model were used to assess the potential and limitations to warm form this alloy.

2. Forming Experiments
The ZEK100 panels were formed using a prototype tooling set, originally developed for warm forming of 5000-series aluminum blanks but using a commercial door inner geometry. The ZEK100 blanks were heated in a contact furnace to temperatures in the range 215–260 °C and then rapidly transferred by robot to the stamping press. Further details regarding the forming experiments are given by Niu et al. [8]. The success of the forming operation was found to be strongly dependent upon the initial blank temperatures. Pre-heat temperatures of 230-260 °C resulted in successful draws (Fig. 1). Above this temperature range, the warm forming lubricant (Fuchs Forge Ease Al278) exhibited excessive smoking, while forming at temperatures below this range resulted in tearing of the blank. Attempts to form AZ31B blanks were unsuccessful for all temperatures considered (up to 300 °C) [8].

![Fig. 1. As-formed door inner panels. Panel on left pre-heated to 215 °C and showed splits (arrow). Panel on right was pre-heated to 230 °C and formed without splits [8].](image)

3. Finite Element Model
The FE models in this work were run using Autoform R7, using a mesh size ranging from 2-10 mm. Fig. 2 shows the finite element mesh used to model the blank. The warm forming operation was set up as a three-step operation, consisting of a heating and transfer step, a drawing step, and a cooling/springback step. The forming speed used was 160 mm/s. The coefficient of friction between the tooling and blank was 0.10, which is representative of Fuchs Forge Ease Al278 lubricant at a temperature of 150 – 200 °C [9]. Two blank start temperatures were modelled: 215 and 230 °C. The transfer time between the furnace to the die set was set to 12s, and the blank sat on the die surface for 3s before the clamping by the binder.
Fig. 2. Finite element model of the door inner stamping operation.

3.1. Constitutive Model

The following constitutive model was proposed by Kurukuri et al. [7] to capture work hardening in ZEK100 as a function of temperature and strain rate:

\[
\bar{\sigma} = C_0 + \left(C_1 + C_2\sqrt{\bar{\varepsilon}}\right) \exp\left[-C_3 + C_4 \ln(\dot{\varepsilon})T\right] + (C_5 - C_6 T) \bar{\varepsilon}^n
\]

This model is based on the Zerilli-Armstrong constitutive model [10]. The calibrated constants for ZEK100, from Kurukuri et al. [7], are shown in Table 1. Fig. 3a shows the experimental stress-strain curves, due to Kurukuri et al. [7], plotted alongside the curves generated using the equation above. Fig. 3b shows the stress-strain curves used in the finite element software, including an extrapolation at 250 °C. For each temperature, stress-strain curves at the following strain rates are shown: 0.001, 0.1, 1, 10 and 100 s⁻¹. The curves in Fig. 3b were input to Autoform.

Table 1. Calibrated parameters for the Zerilli-Armstrong equation, from Kurukuri et al. [7].

| Parameter | Value   |
|-----------|---------|
| \(C_0\) (MPa) | 39.30   |
| \(C_1\) (MPa) | 266.16  |
| \(C_2\) (MPa) | 946.52  |
| \(C_3\) (K⁻¹) | 2.53 \times 10⁻³ |
| \(C_4\) (K⁻¹) | 8.65 \times 10⁻⁵ |
| \(C_5\) (MPa) | 231.34  |
| \(C_6\) (MPa-K⁻¹) | 0.907   |
| \(n\)       | 0.684   |
Fig. 3. (a) Experimental stress-strain curves (by Kurukuri et al. [3]) versus the stress-strain curves fit using the constitutive model, and (b) Stress-strain curves for ZEK100 as a function of temperature and strain rate, generated using the parameters in Table 1. For each temperature, curves are plotted for the following strain rates: 0.001, 0.1, 1, 10 and 100 s\(^{-1}\).

3.2. Yield Surface
Fig. 4 shows the normalized BBC 2005 yield locus that was used in the FE model, alongside yield loci calibrated by Kurukuri et al. [7] at different temperatures. Note that the yield loci calibrated by Kurukuri et al. [7] do capture the tension-compression asymmetry of ZEK100 at each temperature. However, Autoform does not have the capability to model tension-compression asymmetry. In addition, the degree of yield asymmetry is considerably reduced at elevated temperatures due to suppression of twinning [11]. Hence, only the tensile portion of the yield locus calibrated at 200 °C by Kurukuri et al. [7] was used to calibrate the shape of the yield BBC 2005 yield locus. The r-values and other anisotropic properties to achieve the BBC yield surface in Fig. 4 are shown in Table 2, and are due to Kurukuri et al. [3].

It should be noted that Kurukuri et al. [3] found that the r-value of ZEK100 changed with increasing plastic work. However, Autoform does not have the ability to model instantaneous r-values with respect to plastic strain. Therefore, the values shown in Table 2 are the average of all of the r-value vs plastic strain reported by Kurukuri et al. [3].
Fig. 4. The BBC yield locus used in the Autoform model, alongside the yield loci calibrated by Kurukuri et al. [3] at three temperatures.

Table 2. Anisotropic properties of ZEK100, obtained from Kurukuri et al. [3].

| Property          | Value   |
|-------------------|---------|
| R0                | 0.60    |
| R45               | 0.62    |
| R90               | 0.34    |
| $\sigma_{DD}/\sigma_{RD}$ | 0.888 |
| $\sigma_{TD}/\sigma_{RD}$ | 1.112 |
| $\sigma_{biaxial}/\sigma_{RD}$ | 1 (assumed) |
| $R_{biaxial}$     | 1 (assumed) |
| m                 | 8       |

3.3. Heat Transfer

During the transfer, the HTC due to natural convection was set to 17.1 W/m²-K [6]. During the drawing phase, the HTC between the blank and tooling, as a function of contact pressure, was determined using the following equation from Omer et al. [6]:

$$h = 0.004P^3 - 0.5902P^2 + 28.591P + 395.8$$

where $h$ is HTC, in W/m²-K, and $P$ is the contact pressure, in MPa.

For the final step of the warm forming operation, which was the cooling/springback step, the HTC due to natural convection was set to 17.1 W/m²-K, which is the same value as in the furnace-die transfer.

4. FE Model Results

Fig. 5 shows contour plots of predicted wrinkling, plastic strains and temperature at the end of the drawing step of the warm forming operation using a start temperature of 215 °C. Fig. 6 shows the same data for the 230 °C start temperature. For the 215 °C case, the part cooled to between 140-180 °C, during forming whereas for the 230 °C case, the formed part remained above 175 °C. The part formed using a start temperature of 215 °C was predicted to have some splits, whereas the part with 230 °C start...
temperature was not predicted to have splits due to the drop in forming limit with temperature as the part cooled (Fig. 8). Neither part was predicted to experience any significant wrinkling.

Fig. 7 shows a major vs minor strain plot for the 215 °C case and Fig. 8 shows a similar plot for the 230 °C case. Both figures also have forming limit curves (FLCs) obtained from Boba et al. [1] for ZEK100 at three temperatures: 150, 200 and 250 °C.

**Fig. 5.** Contour plots showing predicted wrinkling, plastic strain and temperature in the formed part at the end of the drawing step (but before the cooling/springback step). The results shown are for an initial temperature of 215 °C.

**Fig. 6.** Contour plots showing predicted wrinkling, plastic strain and temperature in the formed part at the end of the drawing step (but before the cooling/springback step). The results shown are for an initial temperature of 230 °C.
Fig. 7. Major vs minor strains in the elements of the part with initial temperature of 215 °C. Also shown are FLCs at three temperatures, which are obtained from Boba et al. [1]. The points in red indicate elements that split.

Fig. 8. Major vs minor strains in the elements of the part with initial temperature of 230 °C. Also shown are FLCs at three temperatures, which are obtained from Boba et al. [1].

5. Discussion and Conclusions
For the door panel modelled in this work, the scenario in which the blank was formed with an initial temperature of 215 °C resulted in splits whereas the blank with an initial temperature of 230 °C formed successfully. The predictions of splitting (or no splitting) for both scenarios match with what was observed in the forming experiments.

The likely cause for the splits in the 215 °C case was that the temperature drop in some regions of the blank resulted in the material FLC dropping to below the applied strains. As evidenced by the FLCs and the element strain distributions in Fig. 7 and Fig. 8, the magnitude of the strains did not change significantly between the two starting temperature cases. However, when the initial temperature of the blank was 230 °C, the strains within the entire blank remained below the 200 °C FLC, allowing for a successful forming operation. In the 215 °C scenario, some elements experienced strains above the 150
°C FLC, and strain points corresponding to those elements are shown in red in Fig. 7. All of the elements shown in red cooled to a temperature below 150°C, placing them in the failure zone of the FLC.

The results of the FE model and the forming experiments show that ZEK100 sheet can be successfully formed using room temperature tooling under some conditions. The main condition for a successful forming operation (i.e., no splits and minimal wrinkling) is that the entire blank needs to be formed at a high enough temperature.

References
[1] Boba M, Butcher C, Panahi N, Worswick M J, Mishra R K and Carter J T 2015 Warm forming limits of rare earth-magnesium alloy ZEK100 sheet Int. J. Mater. Form. 181–91
[2] Antoniswamy A R, Carpenter A J, Carter J T, Hector L G and Taleff E M 2013 Forming-limit diagrams for magnesium AZ31B and ZEK100 alloy sheets at elevated temperatures J. Mater. Eng. Perform. 22 3389–97
[3] Kurukuri S, Worswick M J, Bardelcik A, Mishra R K and Carter J T 2014 Constitutive behavior of commercial grade ZEK100 magnesium alloy sheet over a wide range of strain rates Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 45 3321–37
[4] Abedini A, Butcher C, Nemcko M J, Kurukuri S and Worswick M J 2017 Constitutive characterization of a rare-earth magnesium alloy sheet (ZEK100-O) in shear loading: Studies of anisotropy and rate sensitivity Int. J. Mech. Sci. 128–129 54–69
[5] Muhammad W, Mohammadi M, Kang J, Mishra R K and Inal K 2015 An elasto-plastic constitutive model for evolving asymmetric/anisotropic hardening behavior of AZ31B and ZEK100 magnesium alloy sheets considering monotonic and reverse loading paths Int. J. Plast. 70 30–59
[6] Omer K, Butcher C and Worswick M 2019 Characterization of Heat Transfer Coefficient for Non-Isothermal Elevated Temperature Forming of Aluminum and Magnesium Sheet Int. J. Met. Form.
[7] Kurukuri S, Butcher C and Worswick M J Phenomenological modeling of tension-compression asymmetric response of sheet materials using an interpolation- based yield function
[8] Niu X, Skszek T, Fabischek M and Zak A 2013 Low Temperature Warm Forming of Magnesium ZEK 100 Sheets for Automotive Applications 1–8
[9] Noder J 2017 Characterization and Simulation of Warm Forming of 6xxx and 7xxx Series Aluminum Alloys by (University of Waterloo)
[10] Armstrong R W and Zerilli F J 1994 Dislocation mechanics aspects of plastic instability and shear banding Mech. Mater. 17 319–27
[11] Ishikawa K, Watanabe H and Mukai T 2005 High temperature compressive properties over a wide range of strain rates in an AZ31 magnesium alloy J. Mater. Sci. 40 1577–82