High-temperature Tensile Deformation Behaviour of Aluminium Alloy 2024 and Prediction of Forming Limit Curves

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Abstract. Tensile tests were performed on aluminum alloy 2024 (AA 2024) using a Gleeble-1500 thermal-mechanical simulation system at high temperatures of 350, 400 and 450 °C and strain rates of 0.01, 0.1 and 1 s\(^{-1}\). True stress-strain curves of AA 2024 were obtained. Forming limit curves (FLC) of AA 2024 were theoretically predicted based on Marciniak–Kuczynski (M–K) groove theory. In addition, the predicted curves were validated using the Nakazima method, and the effects of temperature on the FLC were analyzed. The results show that the curves predicted based on the M–K theory were in relatively good agreement with the experimental data. The forming limit of the AA 2024 sheet first increased, reached a maximum at 400 °C, and then decreased as its temperature increased.

1. Introduction
Aluminium alloys (AA) have low densities, high specific strengths and good corrosion resistance, are highly recyclable and recoverable, and can be strengthened by heat treatments; therefore, they are ideal class of materials for manufacturing lightweight machine. However, at room temperature, AAs have relatively poor ductility and cannot be formed into products that are complex in shape and require high precision [1].

As their temperature increases, the plasticity of AA sheets will improve dramatically. Therefore, AA sheets can be formed into components with complex shapes at relatively high temperatures. The forming limit is an important performance metric used in the sheet metal forming field to reflect the maximum deformation of sheet metal before the onset of plastic instability during the forming process. Of the various sheet metal-forming evaluation methods, forming limit curves (FLC) [2] are used most extensively and provide an effective tool for evaluating the formability of sheet metal and addressing its stamping issues.

Ma et al. [3] theoretically predicted the FLC of the Al-lithium alloy 5A90 at various temperatures based on the Marciniak–Kuczynski (M–K) theory and performed a forming limit test on this alloy at 25–300 °C. By combining ductile fracture criteria and the conventional M–K model, Yang et al. [4] proposed a modified M–K model based on ductile fracture criteria and predicted the forming limit of AA 7075-O. Yu et al. [5] introduced the Logan–Hosford yield criterion and the Rossard constitutive equation into the M–K theory and, on this basis, theoretically predicted the forming limit of an interstitial-free steel and discussed the factors affecting its FLC. Hu et al. [6] predicted the FLC of an AA 5754-O sheet based on the M–K theoretical model and analysed the effects of the initial unevenness in thickness and yield function index on the FLC of the alloy sheet.
Chu et al. [7] established a theoretical forming limit prediction model for AA sheets welded using the friction stir welding technique.

All of the aforementioned studies on the forming limit demonstrate the feasibility and accuracy of prediction based on the M–K theory. However, few studies have been conducted to examine 2xxx series AAs with relatively high strength.

In this study, the FLC of AA 2024 were predicted based on the M–K theory and subsequently experimentally validated. Tensile tests were first performed on AA 2024 sheet specimens at high temperatures, and the forming limits were predicted based on the M–K theory and validated using the Nakazima method. This study is of great importance to the engineering application of this alloy.

2. Experimental

2.1. Material

A 2-mm-thick AA 2024 sheet was subjected to tensile tests at high temperatures. Table 1 summarizes the chemical composition of the Al alloy.

| Element | Cu | Mg | Mn | Zn | Fe | Si | Cr | Ti | Al       |
|---------|----|----|----|----|----|----|----|----|---------|
| wt.%    | 4.2| 1.5| 1.3| 0.13| 0.2 | 0.1| 0.06| 0.09| Remaining|

2.2. Thermal tensile tests

The 2-mm-thick AA 2024 sheet was cut into dog-bone-shaped specimens as shown in Figure 1. The specimens were subjected to tensile tests on a Gleeble-1500 thermal-mechanical simulation system at temperatures of 350, 400 and 450 °C and strain rates of 0.01, 0.1 and 1 s⁻¹ until fracture occurred.

Figure 1. Thermal tensile test specimen

Figure 2 shows the true stress-strain curves of the AA 2024 sheet obtained from the tests.

![Figure 2](image)

2.3. True stress-strain curves of AA 2024: (a) 350 °C; (b) 400 °C; (c) 450 °C

3. Forming limit prediction theory
3.1. M–K model

With the assumption that sheet metal is initially inhomogeneous as its core, the M–K theory states that sheet metal, when subjected to planar stretching, is inhomogeneous in the direction (i.e., thickness direction) perpendicular to the direction of the maximum initial stress due to geometric and physical factors and that this inhomogeneity is unavoidable and is represented by a groove (which exists before the sheet metal undergoes deformation). According to this assumption, the central instability of sheet metal is caused by its initial surface defects. The M–K model is extensively used to predict the FLC of sheet metal that undergoes planar deformation by initial defect growth. Figure 3 shows the M–K theoretical model. Regions A and B represent the homogeneous and inhomogeneous regions of the sheet metal, respectively; directions 1 and 2 represent the planar initial stress and strain directions, respectively, and direction 3 represents the vertical initial stress and strain directions; \( t_A \) and \( t_B \) represent the thickness of the sheet metal in regions A and B during the deformation process, respectively.

![Figure 3. Schematic diagram of the M–K model](image)

The M–K theory makes the following assumptions [7]:

1. **Constant volume principle**
   
   \[ \text{d} \varepsilon_1 + \text{d} \varepsilon_2 + \text{d} \varepsilon_3 = 0 \]  
   
   Where \( \text{d} \varepsilon_i (i=1, 2, 3) \) is the strain increment.

2. **Simple loading condition**: both the principal stress and principal strain in region A increase proportionally, and their ratio remains constant.
   
   \[ \frac{\text{d} \sigma_1}{\sigma_1} = \frac{\text{d} \sigma_2}{\sigma_2} = \frac{\text{d} \sigma_3}{\sigma_3} \]  
   
   (2)

3. **Deformation coordination condition**: the secondary principal strain increment in region A is the same as that in region B.
   
   \[ \text{d} \varepsilon_2 = \text{d} \varepsilon_2 = \text{d} \varepsilon_2 \]  
   
   (3)

4. **Force equilibrium condition**: the forces in regions A and B in the primary principal direction are always in equilibrium.
   
   \[ \sigma_{1A} t_A = \sigma_{1B} t_B \]  
   
   (4)

5. **The initial inhomogeneity coefficient** is
   
   \[ f_0 = \frac{t_A^0}{t_B^0} \]  
   
   (5)

   where \( t_A^0 \) and \( t_B^0 \) are the initial thicknesses of the sheet metal in regions A and B, respectively.

3.2. Solving the M–K model
Before deformation occurs, the strains in regions A and B are zero. To facilitate subsequent calculation, a component of the stress in region A, \( \varepsilon_1 \), is set as a known value. At a relatively high temperature, the anisotropy of an AA 2024 sheet decreases, and thus the sheet can be approximated as isotropic. Therefore, its anisotropy is not taken into consideration in the theoretical derivation. Thus, the Mises yield criterion, which assumes that sheet metal is isotropic, is used.

\[
\sigma_i^2 = \frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]
\]  

Let \( \alpha = \frac{\sigma_2}{\sigma_1} \) be the stress ratio and \( \varphi = \frac{\sigma}{\sigma_1} \) be the ratio of the equivalent stress to the maximum principal stress. In the planar stress state, the above equation can be simplified to

\[
\varphi = \sqrt{1 - \alpha + \alpha^2}
\]  

Based on the Mises incremental theory, we have

\[
\frac{\text{d} \varepsilon_1}{2\sigma_1 - \sigma_2 - \sigma_3} = \frac{\text{d} \varepsilon_2}{2\sigma_2 - \sigma_1 - \sigma_3} = \frac{\text{d} \varepsilon_3}{2\sigma_3 - \sigma_2 - \sigma_1} = \frac{\text{d} \varepsilon}{2\sigma}
\]  

Let \( \rho \) be the ratio of the secondary strain to the principal strain.

\[
\rho = \frac{\text{d} \varepsilon_2}{\text{d} \varepsilon_1} = \frac{2\alpha - 1}{2 - \alpha}
\]  

Let \( \beta \) be the ratio of the equivalent strain to the principal strain.

\[
\beta = \frac{\text{d} \varepsilon}{\text{d} \varepsilon_1} = \frac{2\varphi}{2 - \alpha}
\]  

The strain in the normal direction of the thickness of the metal sheet is

\[
\varepsilon_3 = \ln \frac{t}{t_0}
\]  

By combining equations (1), (3) and (4), the equation for regions A and B is obtained.

\[
\bar{\sigma}_A \cdot t_0 \cdot \exp(\varepsilon_A^d) \cdot \phi_B = \bar{\sigma}_B \cdot t_0 \cdot \exp(\varepsilon_B^d) \cdot \phi_A
\]  

Let \( f \) be the unevenness in thickness, and thus, we have

\[
f = f_0 \cdot \exp(\varepsilon^d_B - \varepsilon^d_A)
\]  

By substituting equation (13) into equation (12), and based on the constitutive relationship, equation (12) is transformed to

\[
\left( \bar{\varepsilon}_A \right)^n \cdot (\text{d} \varepsilon_1^d)^m \cdot \phi_B = \left( \bar{\varepsilon}_B \right)^n \cdot (\text{d} \varepsilon_2^d)^m \cdot f \cdot \phi_A
\]  

Where \( \bar{\varepsilon}_A, \bar{\varepsilon}_B, \varepsilon_A^d \) and \( \varepsilon_B^d \) represent the sum of the increments \( \varepsilon_{\text{New}} = \varepsilon_{\text{Old}} + \text{d} \varepsilon \). Based on the known \( \text{d} \varepsilon_1^d, \text{d} \varepsilon_2^d \) can be calculated using the corresponding equation. When \( \frac{\text{d} \varepsilon_2^d}{\text{d} \varepsilon_1^d} \geq 10 \), the ultimate strain corresponding to \( \alpha \) can be calculated by iteration. By using \( \varepsilon_A^d \) and \( \varepsilon_B^d \) as the ultimate principal and secondary strains, respectively, an FLC is plotted.

4. Results and discussion
4.1. Discussion on thermal tensile test results

Figure 2 shows the true stress-strain curves of the AA 2024 sheet obtained from tensile tests at high temperatures. The true tensile stress-strain curves of the AA 2024 sheet conform to the deformation pattern of an ordinary AA. Each true stress-strain curve consists of three sections, namely, an initial plastic deformation section, a stable deformation section and a fracture deformation section. At the same temperature, the flow stress of the alloy gradually increased as the strain rate increased. This is because as the strain rate increased, the internal dislocation density of the alloy increased, and dislocation pile-ups were formed, thereby preventing deformation of the alloy. In addition, due to the increase in the strain rate, the time needed for the alloy to soften decreased, and consequently, the stress of the alloy increased. Moreover, the peak stress of the alloy gradually decreased as the temperature increased. This is because as the temperature increased, the softening mechanism of the alloy became more active, and the dynamic recovery and dynamic recrystallization and softening of the alloy strengthened, resulting in a decrease in its resistance to deformation, which ultimately resulted in a decrease in flow stress.

4.2. FLC predicted by the M–K model

The FLC of the AA 2024 sheet at 400 °C was obtained using the Nakazima method. Figure 4 shows a comparison of the FLC predicted using the M–K theory and the FLC obtained from the experiment. The two curves are in relatively good agreement, suggesting relatively high prediction accuracy.

4.3. Effects of the deformation temperature on FLC

Figure 5 shows the effects of the deformation temperature of the alloy sheet on its FLC. As the temperature increased, the forming limit of the alloy sheet first increased, reached a maximum at 400 °C, and then decreased. This phenomenon is similar to the effects of temperature on the ultimate tensile strain during a uniaxial tensile test.
5. Conclusions
(1) The flow stress of an AA 2024 sheet at temperatures of 350–450 °C and strain rates of 0.01–1 s⁻¹ was analysed through Gleeble tensile tests. The results show that at the same strain rate, the flow stress of the alloy sheet gradually decreased as its temperature increased; at the same temperature, the flow stress of the alloy sheet increased as the strain rate increased.

(2) FLC of the AA 2024 sheet at high temperatures were predicted using the M–K theoretical model, and the predicted curves were validated using the Nakazima method. The predicted curves were found to be in relatively good agreement with the experimental data. The effects of temperature on the FLC were also analysed. The results show that as the deformation temperature increased, the forming limit of the alloy sheet first increased, reached a maximum at 400 °C, and then decreased.

Acknowledgments
This research is financed by National Natural Science Foundation of China (51761030), Natural Science Foundation of Inner Mongolia (2016BS0501).

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