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Theoretical prediction of forming limit diagram of AZ31 magnesium alloy sheet at warm temperatures

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Abstract: A theoretical prediction on forming limit diagram (FLD) of AZ31 magnesium alloy sheet was developed at warm temperatures based on the M−K theory. Two different yield criteria of von Mises and Hill'48 were applied in this model. Mechanical properties of AZ31 magnesium alloy used in the prediction were obtained by uniaxial tensile tests and the Fields−Backofen equation was incorporated in the analysis. In addition, experimental FLDs of AZ31 were acquired by conducting rigid die swell test at different temperatures to verify the prediction. It is demonstrated from a comparison between the predicted and the experimental FLDs at 473 K and 523 K that the predicted results are influenced by the type of yield criterion used in the calculation, especially at lower temperatures. Furthermore, a better agreement between the predicted results and experimental data for AZ31 magnesium alloy sheet at warm temperatures was obtained when Hill'48 yield criterion was applied.

Key words: magnesium alloy; forming limit diagram; theoretical prediction; yield criterion; sheet warm forming

1 Introduction

As a type of lightweight structural material, magnesium and its alloy have broad application prospects in automotive, aerospace, optical equipment and many other areas because of their low density, and high specific strength and stiffness. However, the poor plasticity of magnesium alloys at room temperature severely limits its applications [1]. Nevertheless, studies have shown that the plasticity of magnesium alloys can be significantly improved with the increase of temperature [2,3]. Therefore, research on the formability of magnesium alloys sheet at elevated temperatures is of great importance to the development of its application.

As the simplest and most intuitive tool to assess the formability of magnesium alloys sheet metal, the forming limit diagram (FLD), which is a plot of the maximum major principal strains that can be sustained by sheet materials prior to the onset of localized necking, is a useful concept for characterizing the formability of sheet metals [4]. The FLD is influenced by many factors: sheet thickness, grain size, anisotropy (Lankford coefficient *r*), strain hardening exponent, friction, surface quality, die geometry, strain path and blank holder force [5]. Experimental method and theoretical prediction are the two main methods that can be used to obtain the FLD. CHEN and HUANG [6] determined the FLD of AZ31 magnesium alloy sheets at elevated temperatures by conducting forming limit tests. The conical cup value (CCV) tests reveal that an optimum forming temperature is below 673 K and above 373 K for AZ31 sheets. ZHONG et al [7] obtained the FLD of AZ31 magnesium alloy sheet by performing rigid die swell test at elevated temperatures, and a model of FLD at different temperatures was also developed by fitting the experiment data. MEKONEN et al [8] investigated the mechanical responses of the Nakazima-type sheet forming for the magnesium alloys ZE10 and AZ31 at warm temperature (473 K). Their results revealed that sufficient ductility allows sheet forming processes at the prescribed test temperature. BRUNI et al [9] studied the effect of temperature, strain rate and fiber orientation on the FLD of AZ31 magnesium alloy sheets and concluded that the formability of AZ31 magnesium alloy was improved with increasing temperature and decreasing

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strain rate. LEE et al [10] also studied the effects of temperature and strain rate on the warm formability of AZ31 sheet by experiments and FE analysis. Moreover, BERGE et al [11] investigated the influence of temperature and punch velocity on the forming limit behavior of twin-roll cast, rolled and heat-treated AZ31. Most of the above studies mainly focused on the experimental acquisition of the FLD of AZ31 at different temperatures. However, the theoretical prediction about the FLD of AZ31 at different temperatures was not carried out.

The M−K model, which was proposed by MARCINIAK and KUCZYNSKI [12] based on the assumption of non-uniform thickness, is the most widely used theory to predict FLD of metal sheets at present. Based on the M−K model, CHIBA et al [13] obtained the FLD of AA1100 aluminum alloy sheet using two different ways of phenomenological theory and crystal plasticity theory. LI et al [14] obtained a predicted FLD of aluminum alloy 2B06 by using the M−K model, and the results agreed with the experimental data very well. BUTUC et al [15] performed a theoretical study on forming limit diagrams using a new general code for forming limit strains prediction. The isotropic von Mises criterion, the quadratic Hill criterion (Hill’48), non-quadratic Hill criterion (Hill’79) and Barlat yield function were used in order to illustrate the effects of the shape of the yield locus on the formability. ÁVILA and VIEIRA [16] proposed a new algorithm, and applied it to the FLD predictions of AK steel, aluminum 2036-T4, IF steel and EEP steel with different yield criteria successfully. Nevertheless, compared with experimental method, there are fewer researches on the theoretical prediction of FLD of magnesium alloy sheet.

In this work, the M−K theory was applied by combining two kinds of yield criteria to predict the FLD of AZ31 magnesium alloy sheet at warm temperatures. Uniaxial tensile tests were carried out to obtain the mechanical properties used in the prediction. To verify the applicability of the theoretical prediction, rigid die swell tests were also performed to obtain the practical FLD of AZ31 magnesium alloy sheet. The results of prediction were compared against the experimental data to verify the developed predictive model.

2 Theoretical analysis of FLD

2.1 Uniaxial tensile tests

The mechanical properties are the basic information for the theoretical and numerical studies of the FLD of metal sheets. The uniaxial tensile tests were performed to obtain the mechanical properties of magnesium alloy sheet in a wide range of temperatures and strain rates. Material used in this study is AZ31 magnesium alloy sheet with a thickness of 1 mm, produced by continuous casting and rolling, and its chemical composition is shown in Table 1. Specimens were prepared by wire electrical discharge machine (WEDM) according to the national standard GB4338−2006 (equivalent to ISO 783: 1999) along the rolling direction (Fig. 1). In order to carry out tensile tests at different temperatures, a heating furnace was mounted on the tensile test machine. The specimens were heated to 373, 423, 473, 523, 573, 623 and 673 K, respectively, and held for 10 min to equalize the temperature over the full sample before the tensile tests, and the temperature accuracy is ±5 K. Three thermocouples were connected in the upper, middle and lower gauge areas respectively to measure the temperature of the samples. The initial strain rates were set at 0.001, 0.01 and 0.05 s^{-1}, respectively. Figure 2 shows the influences of test temperatures and strain rates on the flow stress−strain curve respectively. It can be seen from Fig. 2(a) that both the yield and tensile strengths decrease sharply with increasing the test temperature. When the temperature exceeds 423 K, work hardening in the plastic deformation stage is not obvious and the plasticity of AZ31 magnesium alloy is improved significantly. It can be attributed to the dynamic recovery, continuous dynamic recrystallization, grain boundary sliding and the activational slip systems at high temperatures [5]. At low temperatures, strong hardening occurs in the early stages of deformation below the ultimate tensile strength, which is related to dislocation hardening in combination with a rising degree of twinning. It can be seen from Fig. 2(b) that the ductility of AZ31 magnesium alloy sheet decreases significantly with the increase of strain rate, especially at higher test temperatures. This is in accordance with the result of ULACIA et al [17], who suggested that the decrease of critical resolved shear stress (CRSS) of nonbasal slip is less distinct at high strain rates than that at low strain rates.

Table 1 Composition of AZ31 magnesium alloy sheet (mass fraction, %)

Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
3.18	1.02	0.34	0.002	0.022	0.0021	0.00085	Bal.

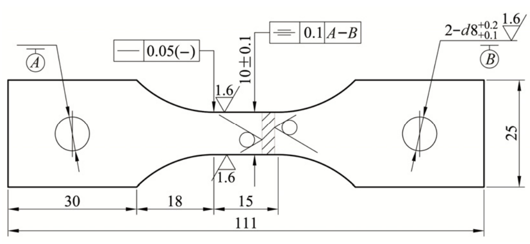

Fig. 1 Shape and dimension of specimen for uniaxial tensile tests (unit: mm)

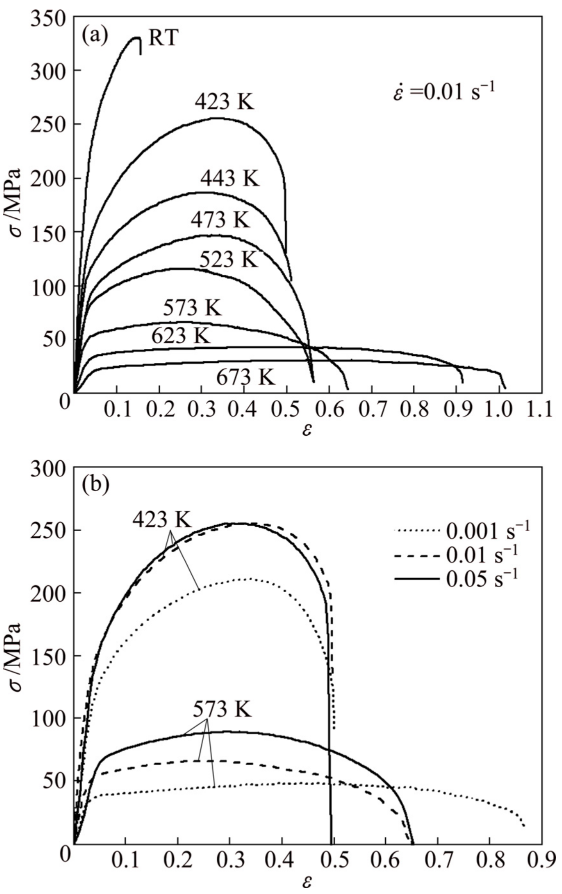

Fig. 2 True stress−strain curves of AZ31 magnesium alloy sheet under different temperatures (a) and strain rates (b)

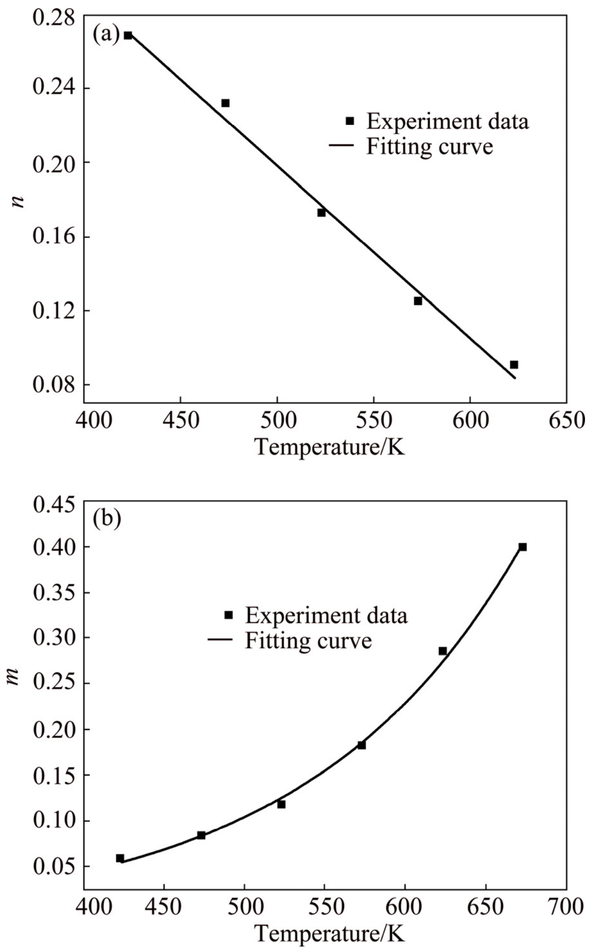

Fig. 3 Variation of strain hardening exponent n (a) and strain rate sensitivity index m (b) with testing temperature of AZ31

In this study, the Fields−Backofen [18] equation was considered to describe the work hardening of the material.

$$\sigma_i = K\varepsilon_i^n \dot{\varepsilon}_i^m \tag{1}$$

where σ_i and ε_i are the effective stress and effective strain, respectively; $\dot{\varepsilon}_i$ is the strain rate; K, n, m are material parameters varying with the temperature and the values of n and m at different test temperatures can be calculated based on the true stress−strain curves. During the FLD tests, the punch velocity is 5 mm/min, with the sheet thickness of 1 mm, the initial strain rate is approximate to 0.01 s^{-1}, hereafter in the prediction of FLD the stain rate is also set to 0.01 s^{-1}. The variation of n and m with temperature at the strain rate of 0.01 s^{-1} was obtained by curve-fitting (see Fig. 3).

$$n=0.6649-9.3\times10^{-4}T \tag{2}$$

$$m=-0.0082+0.0026\exp(T/132.9258) \tag{3}$$

where the value of n decreases linearly with increasing temperature, but the value of m increases exponentially with increasing temperature. In Fig. 3(a), the experimental data of stain hardening index n at the strain rate of 0.01 s^{-1} can be obtained by the Ludwik equation which has the same form as Eq. (1), where σ_i can be gained from the intercept of the strain−hardening portion of the stress−strain curve and the elastic modulus line. The experimental data of the strain-rate sensitivity m in Fig. 3(b) are determined by measuring the change in flow stress brought about by a change in strain rate at certain test temperatures by Eq. (1).

Anisotropic parameter of the material, R, is also a necessary parameter for mechanical properties that is used in both theoretical and numerical studies of sheet metal forming. In order to obtain the value of R, another series of uniaxial tensile tests were conducted according to the national standard GB5027−2007 (equivalent to ISO 10113:2006, IDT) and the test pieces were prepared at 0°, 45° and 90° to the rolling direction, respectively. During the test, stretching was stopped when the strain in the specimen reached 0.1. The value of R can be calculated as follows:

$$R = \ln\left(\frac{b}{b_0}\right) / \ln\left(\frac{L_0 b_0}{Lb}\right) \tag{4}$$

where L and b are the gauge length and width after deformation, respectively, and L_0 and b_0 are initial gauge length and width, respectively. The normal plastic anisotropy is defined as

$$\overline{R}=\frac{R_0+2R_{45}+R_{90}}{4} \tag{5}$$

where R_0, R_{45} and R_{90} are R-values determined from uniaxial tests at 0°, 45° and 90° to the rolling direction, respectively.

Values of $\overline{R}$ obtained at different temperatures are listed in Table 2. It can also be seen that as temperature increases, the value of $\overline{R}$ decreases and the degree of anisotropy of the sheet reduces with increasing temperature.

Table 2 Values of $\overline{R}$ at different temperatures

Temperature/K	R_0	R_{45}	R_{90}	$\overline{R}$
473	1.3	1.9	1.5	1.65
523	0.8	1.2	1.1	1.075

2.2 M−K model

In the M−K model, an imperfection or non-homogeneity is responsible for progressive strain concentration until the occurrence of failure by localized necking [19]. It was assumed that strain localization is a continuous process originating from preexisted defects in the material. To simplify the analysis, the defects in the material are interpreted as a long groove perpendicular to the direction of the major principal stress and a schematic of M−K model is shown in Fig. 4. The mark a and b represent the uniform and the groove region respectively. During the whole calculation, it was assumed that:

1) The strains parallel to the groove are the same in both inner and outer regions, i.e.,

$$\mathrm{d}\varepsilon_{2a}=\mathrm{d}\varepsilon_{2b} \tag{6}$$

2) The forces perpendicular to the groove must keep balance, i.e.,

$$\sigma_{1a}t_a=\sigma_{1b}t_b \tag{7}$$

The isotropic von Mises yield criterion [20] and the quadratic Hill'48 yield criterion [21] were applied to predicting the FLD of AZ31 magnesium alloy sheet at warm temperatures.

1) von Mises yield criterion

It is assumed that in the plane stress condition, von Mises yield equation is given by

$$2\sigma_i^2=\sigma_1^2+\sigma_2^2+\left(\sigma_1-\sigma_2\right)^2 \tag{8}$$

where σ_i is equivalent stress, σ_1 and σ_2 are the principal stresses, respectively.

2) Hill'48 yield criterion

To take the anisotropy of the sheet into account, Hill'48 yield function was employed. Assuming the plane stress condition and the general principal stress notation, Hill'48 yield function is represented by

$$(\overline{R}+1)\sigma_i^2=\sigma_1^2+\sigma_2^2+\overline{R}(\sigma_1-\sigma_2)^2 \tag{9}$$

where $\overline{R}$ is the normal plastic anisotropy. It is obvious that the von Mises yield criterion is a particular case of Hill'48 yield criterion when $\overline{R}$=1.

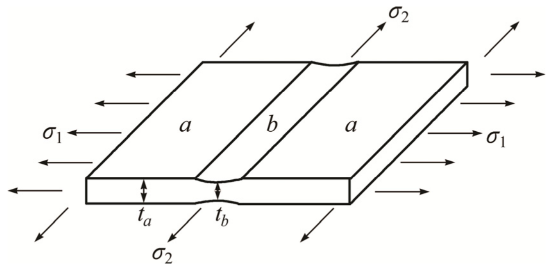

Fig. 4 Schematic of M−K model

2.3 Theoretical prediction of FLD

In this study, the method proposed by GRAF and HOSFORD [22] is adopted and the hardening effects are represented by Eq. (1). According to this methodology, Eq. (9) can be rewritten as

$$\left(\varepsilon_{ia}+\Delta\varepsilon_{ia}\right)^n\left(\frac{\beta_a}{\rho_a}\right)^m\left(\frac{1}{\varphi_a}\right)=\left(\varepsilon_{ib}+\Delta\varepsilon_{ib}\right)^n\left(\frac{\beta_b}{\rho_b}\right)^m\left(\frac{1}{\varphi_b}\right)f\exp\left(\varepsilon_{3b}-\varepsilon_{3a}\right) \tag{10}$$

where φ is the ratio of the effective stress to the major principal stress, f stands for the initial thickness imperfection, ρ represents the ratio of minor to major strain rates, and the ratio of the effective strain variation to the major strain increment is given by β. α is defined as the ratio of the second principal stress to the major principal stress. Mathematically, all the parameters are listed as

$$\varphi=\frac{\sigma_i}{\sigma_1},\ f=\frac{t_{b0}}{t_{a0}},\ \rho=\frac{\mathrm{d}\varepsilon_2}{\mathrm{d}\varepsilon_1}=\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1},$$
$$\beta=\frac{\mathrm{d}\varepsilon_i}{\mathrm{d}\varepsilon_1}=\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_1},\quad \alpha=\frac{\sigma_2}{\sigma_1} \tag{11}$$

The values of φ, ρ and β are specific for different yield criteria and β is generally calculated by

$$\beta=\frac{1+\alpha\rho}{\varphi} \tag{12}$$

From Eq. (11) and the incremental theory namely Levy−Mises, it is possible to obtain an expression of φ as

$$\varphi=\left[\frac{1+\alpha^2+\overline{R}(1-\alpha)^2}{\overline{R}+1}\right]^{1/2} \tag{13}$$

The flow rule leads to

$$\rho=\frac{\alpha-\overline{R}(1-\alpha)}{1+\overline{R}(1-\alpha)} \tag{14}$$

Also, Eqs. (13) and (14) reduce to the expression of φ and ρ for von Mises yield criterion when $\overline{R}=1$.

Combining Eq. (10) with the iterative computation method proposed by GRAF and HOSFORD [22], the forming limit under a certain stress condition was calculated through the computer programming, and the FLD was obtained by joining the forming limit points calculated under different stress conditions to a smooth curve.

3 Experiment of FLD

The forming limit diagram of AZ31 magnesium alloy sheets at warm temperatures was obtained experimentally by the rigid die swell test to verify the theoretical prediction. The major testing apparatus was developed by Beijing University of Aeronautics and Astronautics. To find the limiting strain, the length of specimens was 160 mm in the rolling direction and the width varied between 20 and 180 mm in the step of 20 mm which controlled the strain path spans from uniaxial tension to equi-biaxial tension. Circle grids with diameter of 2.5 mm were printed onto the surface of specimens by using the electrochemical etching method in case of the grids to be illegible after heat treatment [23].

The test specimens were heated together with the die to the expected temperature of 423−523 K and held at the test temperature for 10 min to equalize the temperature over the whole chamber. The lubrication between the punch and the sample was established by using colloidal graphite to make sure that the fracture occurs in the center of the specimens. During the test, the specimens were clamped on their edges with a blank holder force of 50 kN and stretched by a hemispherical punch with a diameter of 100 mm at a velocity of 5 mm/min. The strain analysis of the specimens was conducted by means of the GMA (grid measurement and analysis) system, by which local strains on the samples were measured after the test. Then, FLDs were drawn from positions of safe limiting strains from the unsafe zone containing the necked and fractured ellipses [23].

4 Results and discussion

Figure 5 shows a comparison between the predicted FLD and experimental data at 473 and 523 K. The value of f was chosen considering agreement between theoretical and experimental data in plane strain condition. According to MA et al [24], the forming limit curve declines with decreasing of initial thickness heterogeneity parameter, f. While the downtrend becomes weakened gradually, f tends to be a fixed value. Thus, it can be used with a value instead of the f parameter when the degree of initial uneven thickness is small, which will not have influence on the prediction of forming limit diagram. In this study, the f-value is 0.95 at elevated temperatures. It is obvious from Fig. 6 that the forming limit strain of AZ31 magnesium alloy sheet increases with the rise of temperature. The type of yield criterion used in the theoretical prediction makes little difference to left part of FLD, but greatly affects the shape of curve of the right part. For the right part, the theoretical FLD based on von Mises yield criterion is higher than that based on Hill'48 criterion; a higher value of $\overline{R}$ leads to a more obvious difference between the predicted results.

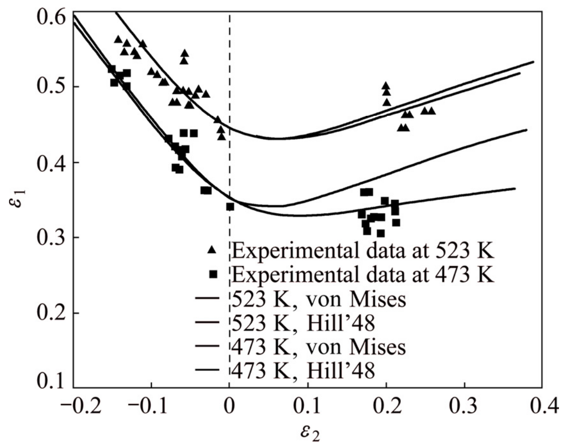

Fig. 5 Comparison of yield criteria and experimental data at 473 and 523 K

On the other hand, as von Mises yield criterion could be regarded as a particular case of Hill'48 criterion at $\overline{R}=1$, it is found obviously that when the value of $\overline{R}$ increases, the anisotropy of the sheet is more notable, the major strain of the sheet becomes smaller in the right part of FLD, but the curve slightly declines in the left part. This is because the fiber texture parallel to the orientation of major principal stress improves the formability of the sheet in uniaxial tension condition, but greatly reduces the forming limit strain in biaxial tension condition.

At 473 K, the predicted results based on Hill'48 yield criterion agreed better with the experimental data. But at 523 K, both von Mises and Hill'48 yield criteria lead to good results, where the value of $\overline{R}$ is close to 1 at 523 K. Therefore, Hill'48 yield criterion seems to be more appropriate for the theoretical prediction of FLD of AZ31 magnesium alloy sheet at warm temperatures.

To verify the computing models based on Hill’48, yield criterion is suitable for the FLD prediction of AZ31 magnesium alloy sheet at warm temperatures, another theoretical prediction was carried out. The material properties and experimental data of FLD were obtained by CHANG [25], except normal plastic anisotropy. The value of normal plastic anisotropy of the sheet used here was the same as above. AZ31 commercially extruded plate with a thickness of 1.2 mm was used in the tests. A comparison between predicted FLD by applying Hill’48 yield criterion and experimental data obtained by CHANG [25] at 523 K (n=0.199, m=0.011, R=1.075) is shown in Fig. 6. It can be seen that the predicted FLD curve is located in the critical region of experimental data of FLD, showing a good agreement between analytical and experimental results.

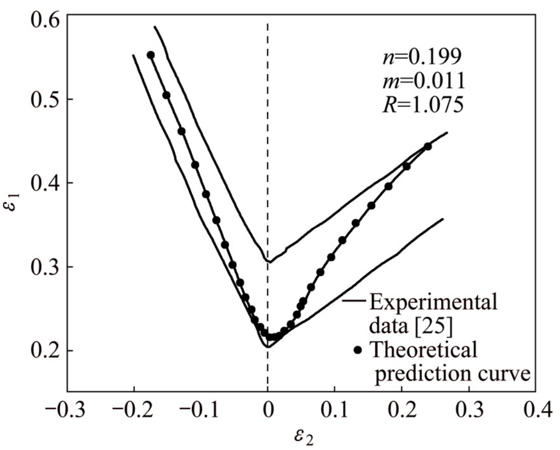

Fig. 6 Comparison between theoretical prediction FLD curve and experimental data obtained by CHANG [25]

5 Conclusions

1) Mechanical properties of AZ31 magnesium alloy sheet were obtained by uniaxial tensile test at warm temperatures. The variations of strain hardening exponent n and strain rate sensitivity index m in the constitutive equation namely Fields−Backofen with the temperature were determined. As the temperature increased, the value of n decreased, but the value of m increased.

2) The type of yield criterion used in the calculation strongly influenced the shape of predicted FLD, especially at lower temperatures. The type of yield criterion made little difference in the left part of FLD, but greatly affected the shape of curve in the right part. The value of normal plastic anisotropy $\overline{R}$ also influenced the predicted results when Hill’48 yield criterion was used. When the value of $\overline{R}$ increased, the forming limit strain of the sheet was lowered in the right part of FLD, but the curve was slightly raised in the left part.

3) The comparison between the predicted FLD and experimental data at 473 and 523 K showed that Hill’48 yield criterion is to be more appropriate for the theoretical prediction of FLD of AZ31 magnesium alloy sheet at warm temperatures.

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AZ31 镁合金板温热状态下成形极限图的理论预测

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摘 要：基于刚塑性材料在平面应力条件下变形的 M−K 理论对 AZ31 镁合金在温热状态下的成形极限图(FLD)进行了预测，在理论预测时采用 von Mises 和 Hill’48 屈服准则。通过单向拉伸实验获得所用的 AZ31 镁合金板的力学性能，同时在分析时引入 Fields−Backofen 本构方程。此外，采用刚性凸模胀形方法获得了 AZ31 镁合金板在不同温度下的实验 FLD 曲线用以验证理论预测结果。通过对 473 K 和 523 K 下理论预测 FLD 与实验 FLD 间的比较，发现理论预测结果受计算时所采用的屈服准则的影响，特别是在温度较低时。采用 Hill’48 二次型各向异性屈服准则获得的 FLD 与实验数据有较好的一致性。

关键词：镁合金；成形极限图；理论预测；屈服准则；板材温热成形

(Edited by Xiang-qun LI)