Determination of forming limit for aluminium alloy sheet eliminating the interferences of through-thickness stress and non-linear strain path

Zhu Chen\textsuperscript{1,2}, Gang Fang\textsuperscript{1,2} *

\textsuperscript{1} Department of Mechanical Engineering, Tsinghua University, Beijing, 100084, China

\textsuperscript{2} State Key Lab of Tribology, Beijing, Tsinghua University, 100084, China

* Corresponding author, e-mail: fangg@tsinghua.edu.cn

Abstract. The accuracy of the forming limit diagram (FLD) determined through Nakazima test is often influenced by non-linear strain path (NLSP) and through-thickness stress. The influence of these factors on measurement accuracy can be weakened or avoided in Marciniak test. But meanwhile, Marciniak test is difficult in operation and possesses poor repeatability. Therefore, the Nakazima test eliminating the influencing factors of accuracy is still an attractive method due to the easy operability and good repeatability. In the present research, two FLDs of aluminium alloy 6014-T4 that were established through Nakazima and Marciniak tests were compared. In order to obtain an accurate FLD in plane-stress state and linear strain paths via Nakazima test, a modified compensation method was applied in Nakazima test to eliminate the interferences of NLSP and through-thickness stress on measuring forming limits. The ultimate strains measured in Nakazima test were transformed to stress-based forming limits through constitutive models to remove the influence of through-thickness stress. Then, the corrected ultimate stresses were transformed back to the limit strains along linear strain paths. Compensated results of Nakazima test showed a good agreement with the experimental results from Marciniak test, proving the validity of this method. Thus, through the easy-operate Nakazima test, an FLD with comparable accuracy to that based on Marciniak test was established.

1. Introduction

In the recent years, the growing demand on weight reduction in the automotive industry has increased the application of lightweight materials, for example, aluminium alloy sheets, in automotive body panels. It is crucial to determine the forming limits of aluminium sheets due to their lower formability compared to traditional steel sheets. The forming limit diagram (FLD) is a commonly used tool for evaluating the formability of sheet metals and predicting forming failures during finite element (FE) simulations of sheet metal stamping process.

Commonly used methods for determining an FLD experimentally can be divided into two types. One is the out-of-plane method represented by Nakazima test where a hemispherical dome punch is utilized, the other is the in-plane method represented by Marciniak test where a flat-top punch is used. It is widely recognized that these two standard tests do not lead to an identical FLD for the same material [1-3]. Nakazima test is complicated by the interferences of friction, through-thickness stress and non-linear strain path, whereas the in-plane Marciniak test avoids these disadvantages. Therefore, the latter has
been suggested as a better tool for establishing an accurate FLD which can distinguish the formability based on inherent material behaviour. However, Marciniak test is sensitive to material internal defects, and premature failure often occurs at the die entry radius during the tests, which is not expected. Therefore, it requires more cautious operation and more sophisticated die setup to ensure the success and reliability of tests, limiting the application of this test method.

The present work aims to establish an accurate FLD in plane-stress state and linear strain paths via easy-operate Nakazima test instead of Marciniak test. A modified compensation method was applied in Nakazima test to eliminate the interferences of NLSP and through-thickness stress on measuring forming limits. The validity of the results was checked by the measured FLD via Marciniak test.

2. Experimental procedure and results

The studied material was aluminium alloy 6014 sheet in T4 temper condition (AA6014-T4) with a thickness of 0.9 mm, which is one of the most commonly used Al-Mg-Si alloys for car body outer panels. Both Nakazima test and Marciniak test were conducted for this material on an in-house developed sheet forming machine by changing the die setup. Figure 1 shows the experiment setup and the dimensions of tools. The geometries of the samples designated in the ISO 12004-2 [4] were used, and the dimensions used in Nakazima and Marciniak tests are summarized in Table 1. A 3-D DIC (Digital Image Correlation) system was employed to record the deformation of samples during tests. Note that a stainless steel sheet with a thickness of 1.0mm was used as carrier blank for every Marciniak test of 1# ~ 4# samples. The functions of carrier blank were to facilitate a more homogeneous strain distribution in the measured areas of samples and ensure that the failure of the tested sample occurred in the expected position. The carrier blank held the same shape as the tested sample and had a central hole of diameter 20mm.

![Figure 1. Experiment setup (a) and dimensions of tools for (b) Nakazima test and (c) Marciniak test.](image)

| Test No. | Sample width (mm) |
|----------|-------------------|
| 1#       | 100               |
| 2#       | 80                |
| 3#       | 60                |
| 4#       | 50                |
| 5#       | 30                |
| 6#       | 20                |
| 7#       | 10                |

There are many different DIC measurement procedures for identifying the onset of localized necking. In the present research, the linear best-fit approach [5-6] was selected since it is concluded to be the
most reliable one with a better estimation of the limit strain at the onset of necking [7-8]. It is based on the variation of thinning rate \( \dot{\varepsilon}_t \) (the first derivative of the thickness strain \( \varepsilon_t \) versus time) of the maximum major strain point at the last frame before the failure. Two linear fittings are conducted and the intersection reveals the onset of necking. Take 2# sample in Marciniak test as an example to show the details, as illustrated in Figure 2. Figure 3 demonstrates two FLDs obtained via Nakazima test and Marciniak test, respectively. Comparison of two FLDs indicated that the forming limits of Nakazima test was higher than that of Marciniak test, and the FLD\(_0\) in Nakazima test shifted a little to the right. This result was consistent with the observations of other research [2-3, 9].

Figure 2. DIC data analysis for 2# sample in Marciniak test using linear best-fit approach.

Figure 3. Comparison of FLDs obtained from Nakazima test and Marciniak test.

Figure 4. Strain paths and the limit strains at the onset of necking in (a) Nakazima test and (b) Marciniak test.

The strain paths of failure points in both tests are shown in Figure 4. It was obvious that the strain paths in Marciniak test were nearly linear from zero strain up to the onset of necking while in Nakazima test they were bowed and there existed biaxial strains initially. In theory, the FLD is (or should be) determined by straining the samples in straight strain paths proportionally, and the shift of FLD\(_0\) in
Nakazima test is commonly believed to be caused by the initial biaxial pre-straining [2, 10-12]. Thus it is important to eliminate NLSP in Nakazima test, either through improving experimental conditions or via data compensation.

Among those factors appeared to contribute to the NLSP, what could be changed in a given Nakazima test was the lubrication. With the aid of finite element simulation of forming process, the role of friction was investigated qualitatively. The disk sample (1#) and the nearly uniaxial tension sample (7#) were representative. The coefficients of friction (COF) between the test sample and the punch were chosen as 0.3 and 0.03 to imitate poor and good lubrication conditions, respectively. The simulation results are shown in Figure 5.

![Figure 5. Simulation results of (a) 1# sample and (b) 7# sample in Nakazima test.](image)

It was found that the friction influenced the failure location and the strain path of failure point. It is recommended in ISO standard to make the failure occur as close as possible to the pole where the strain path is in accord with the expected strain path imposed by the sample geometry. However, the pole remained the same strain path with the most significant biaxial tension pre-strains regardless of the lubrication condition, as the green lines showed in Figure 5 (b). Thus, under well-lubricated condition, the failure occurred at the pole along the expected strain path, but there still existed remarkable initial pre-strain. It is surmised that the NLSP is caused by the ineluctable inherent bending behaviour [2] in Nakazima test rather than the friction. That is to say, it is hard to obtain linear strain paths in Nakazima test by means of improving experimental conditions. Therefore, a data compensation method is necessary to eliminate the interference of NLSP for the FLD of Nakazima test.

Besides the NLSP, another major difference between Nakazima test and Marciniak test was the through-thickness stress, which was reported to influence the onset of necking significantly [13-14]. There existed remarkable through-thickness stress in Nakazima test, and it was sensitive to the dimensions of tools. However, in industrial sheet forming process, the sheets are commonly considered to be formed under plane stress state. Moreover, the through-thickness stress of the widely accepted and used shell element is assumed to be zero in sheet forming simulations. Therefore, the FLD obtained under plane stress condition is more realistic and more suitable for application. It is also necessary to remove the effect of through-thickness stress on the measurement results of Nakazima test.

3. Correction procedure

The compensation method proposed by Min et al. [15] was modified and adopted in the present work to eliminate the interferences of NLSP and through-thickness stress on forming limits determination.

In fact, the method of Min et al. also considers about the effect of curvature by bending. He defines that localized necking occurs on curved sheet metal only when the stresses on all through-thickness layers exceed the instability criterion. That is to say, it is the stress condition on the least critical layer
that controls the onset of necking. The result shows that the middle surface has the lowest bound of path-corrected strain limits among all layers and thus is selected as the control layer for the identification of necking. However, from Min’s published paper, we found that the differences of the limit strains on the middle surface and on other layers were so slight that it could be negligible, compared to the change on limit strains with correction for NLSP and through-thickness stress. Moreover, it is the strain distribution on the outer surface that the DIC detected directly. The strain path on the middle layer has to be determined through complex calculation which indeed needs a great deal of effort. Such a slight difference is not worth the great effort. Therefore, the present work used the limit strains on the outer surface to represent that on the middle surface to simplify the curvature correction.

3.1. Correction for NLSP interference

The correction for NLSP was based on the strain path insensitivity of stress-based forming limit prediction [16]. Combined with the constitutive models of the tested alloy, it is possible to use the measured strain path data to calculate the corresponding stress conditions. The corrected limit strains along an assumed linear strain path was identified when the corresponding calculated stress reached the same limit stress condition at the necking point of the as-measured non-linear strain path. In fact, the calculated procedure could be simplified by removing the hardening law, i.e. identified the forming limit in terms of critical effective strain instead of limit stress, because the effective stress and the effective strain are corresponding during the loading according to the hardening law of materials. In the present method, Hill 48 quadratic yield function for normal anisotropy was used to calculate the equivalent stress or strain, as given by,

\[
\bar{\sigma}_r(\sigma_1, \sigma_2) = \sqrt{\sigma_1^2 + \sigma_2^2 - \frac{2\bar{F}}{1 + \bar{F}}} \sigma_1 \sigma_2
\]

(1)

where \(\bar{F}\) is averaged normal anisotropy coefficient, and \(\sigma_1\) and \(\sigma_2\) are the in-plane major and minor stresses, respectively. The equation for the effective strain rate \(\dot{\varepsilon}\) corresponding to this quadratic yield function is as following:

\[
\dot{\varepsilon}(\dot{\varepsilon}_1, \dot{\varepsilon}_2) = \frac{1 + \bar{F}}{\sqrt{1 + 2\bar{F}}} \sqrt{\dot{\varepsilon}_1^2 + \dot{\varepsilon}_2^2 + \frac{2\bar{F}}{1 + \bar{F}} \dot{\varepsilon}_1 \dot{\varepsilon}_2}
\]

(2)

where \(\dot{\varepsilon}_1\) and \(\dot{\varepsilon}_2\) are the major and minor strain rates, respectively. In general, the effective strain \(\bar{\varepsilon}\) is defined by the integral of \(\dot{\varepsilon}\) with respect to time. Here it is defined in terms of the sum of effective strain increments \(\Delta \dot{\varepsilon}\) since the strain data obtained from DIC images frame by frame was discrete. The effective strain increments are obtained by replacing the strain rate variables \((\dot{\varepsilon}_1, \dot{\varepsilon}_2)\) in Equation (2) with the strain increment variables \((\Delta \varepsilon_1, \Delta \varepsilon_2)\), as shown in Equation (3). And the effective strain is expressed by Equation (4).

\[
\Delta \bar{\varepsilon}(\Delta \varepsilon_1, \Delta \varepsilon_2) = \frac{1 + \bar{F}}{\sqrt{1 + 2\bar{F}}} \sqrt{\Delta \varepsilon_1^2 + \Delta \varepsilon_2^2 + \frac{2\bar{F}}{1 + \bar{F}} \Delta \varepsilon_1 \Delta \varepsilon_2}
\]

(3)

\[
\bar{\varepsilon} = \sum_{j=1}^{N} \Delta \bar{\varepsilon}(\Delta \varepsilon_{1,j}, \Delta \varepsilon_{2,j})
\]

(4)

According to Min et al. [15], the corrected limit strains along a perfectly linear path \((\dot{\varepsilon}_1^*, \dot{\varepsilon}_2^*)\) are calculated by Equation (5).

\[
\begin{pmatrix}
\dot{\varepsilon}_1^* \\
\dot{\varepsilon}_2^*
\end{pmatrix} = \begin{pmatrix}
\Delta \varepsilon_{1,N} \\
\Delta \varepsilon_{2,N}
\end{pmatrix} \frac{\bar{\varepsilon}}{\Delta \bar{\varepsilon}(\Delta \varepsilon_{1,N}, \Delta \varepsilon_{2,N})}
\]

(5)
which means that the assumed linear strain path is defined by the ratio of major and minor strain increments ($\Delta \varepsilon_{1,N}/\Delta \varepsilon_{2,N}$) at the onset of necking ($j = N$). However, as shown in Figure 4 (a), the measured strain paths were bowed and the strain state around the necking drifted towards plane strain state. Therefore, $\Delta \varepsilon_{1,N}/\Delta \varepsilon_{2,N}$ could not represent the main trend of strain path. Here we took the ratio of the average strain increments (Equation (6)) of the nearly linear part of the measured strain path as the assumed linear path, as solid straight lines showed in Figure 6. The linear portion was determined according to the goodness of fit ($R^2$). We chose as much data as possible to fit under the premise that $R^2$ was greater than 0.99.

$$
\left( \frac{\varepsilon_1^*}{\varepsilon_2^*} \right) = \left( \frac{\Delta \varepsilon_{1,avg}}{\Delta \varepsilon_{2,avg}} \right) \Delta \varepsilon\left( \frac{\Delta \varepsilon_{1,avg}}{\Delta \varepsilon_{2,avg}} \right)
$$  \hspace{1cm} (6)

The FLDs of Nakazima test after NLSP correction through Min’s method and the present work are compared with the as-measured one in Figure 7. For the biaxial tension samples 1# and 2#, the corrected limit strains determined by average linear strain path remained biaxial tension strain paths while the results determined by Min’s method drifted seriously towards plane strain state, indicating our results were superior to theirs. Moreover, it was seen that after the correction for NLSP, the FLD$_0$ shifted back to the position representing the plane strain state and the FLC shifted upper wholly. This change trend was consistent with the investigation result that the pre-straining in biaxial tension made the FLD$_0$ shift to the right and lowered the forming limits [10-11].

3.2. Correction for through-thickness stress interference

It has been demonstrated both theoretically and experimentally that through-thickness pressure delays the onset of necking [10, 13]. The correction for the interference of through-thickness stress was realized by subtracting the through-thickness stress from the limit stresses. The through-thickness stress results from the contact on the interface between the sheet and the punch, and the pressure $P$ on the contacting surface is calculated through Equation (7).

$$
P = \mu k \left( 1 + \frac{1}{2} k \right) \left( \sigma_1 + \sigma_2 \right)
$$  \hspace{1cm} (7)
where \( t \) is the thickness of tested sheet, \( k \) is the curvature of the hemispherical punch. The stress components \((\sigma_1, \sigma_2)\) are calculated based on an isotropic hardening law (Hockett-Sherby law):

\[
\bar{\sigma} = \sigma_{sat} - (\sigma_{sat} - \sigma_r) \exp\left[-a\left(\bar{\varepsilon}_p\right)^q\right]
\]

where \( \sigma_{sat}, \sigma_r, a \) and \( q \) are parameters calibrated by fitting measured data of an uniaxial tension. \( \bar{\varepsilon}_p \) is the effective plastic strain, and it is assumed to be replaced by the total effective strain \( \bar{\varepsilon} \) since elastic contribution is negligible.

Considering the contact pressure is unevenly distributed in the thickness direction of the sheet, with the maximum value \( P \) on the contact inner surface and the minimum value zero on the outer surface, an average value \( P/2 \) corresponding to the middle surface was subtracted from the limit stress components to obtain a new limit stress state. Then this new limit stress was transformed back to the strain space to get the corrected limit strains, thus, the interference of through-thickness stress was eliminated. Details of the correction process are schematically shown in terms of a flow chart in Figure 8.

**Figure 8.** Flow chart of the correction process for through-thickness stress interference.

**Figure 9.** Comparison between the limit strains measured by Marciniak test and the corrected measurement by Nakazima test.
The corrected results from Nakazima test are compared with the experimentally determined FLD from Marciniak test in Figure 9. It was seen that the additional correction for through-thickness stress interference lowered the forming limits significantly, and resulted an FLD which was effectively identical with the measured one via Marciniak test, indicating the validity of correction methods. Thus, with this data compensation method, we could obtain a more realistic FLD under linear strain paths and plane stress condition via Nakazima test instead of Marciniak test, and this FLD reflects a true material formability without the interferences of NLSP and through-thickness stress.

4. Conclusions

During the establishment of an FLD, the strain measurement through Nakazima test is easy to be interfered by experimental conditions. Among these affecting factors, NLSP changed the position of FLDs and the through-thickness stress suppressed the onset of necking. To obtain an accurate FLD comparable to the one from Marciniak test, a compensation method for the measured strains from Nakazima test was modified and adopted. It was used to eliminate the interferences of NLSP and through-thickness stress. The compensated results showed a good agreement with the experimental results from Marciniak test, proving the validity of this method. If we want to replace Marciniak test with the easy-operate Nakazima test, further work is needed to improve the lubrication condition in Nakazima test to ensure that the failure occurs at the pole of the tested sample. Thus the strain paths are prone to the expected linear strain paths and the covered strain range will be as wide as in Marciniak test, i.e. from equal biaxial tension to uniaxial tension.

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