Forming Limit Stress Diagram Prediction of Aluminum Alloy 5052 Based on GTN Model Parameters Determined by In Situ Tensile Test

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Abstract

The conventional forming limit diagram (FLD) is described as a plot of major strain versus minor strain. However, FLD is dependent on forming history and strain path. In the present study, a forming limit stress-based diagram (FLSD) has been adopted to predict the fracture limit of aluminum alloy (AA) 5052-O1 sheet. Nakazima test is simulated by plastic constitutive formula derived from the modified Gurson-Tvergaard-Needleman (GTN) model. An in situ tensile test with scanning electron microscope (SEM) is proposed to determine the parameters in GTN model. The damage evolution is observed and recorded, and the parameters of GTN model are identified through counting void fraction at three damage stages of AA5052-O1. According to the experimental results, the original void volume fraction, the volume fraction of potential nucleated voids, the critical void volume fraction, the void volume fraction at the final failure of material are assigned as 0.002 918, 0.024 9, 0.030 103, 0.048 54, respectively. The stress and strain are obtained at the last loading step before crack. FLSD and FLD of AA5052-O1 are plotted. Compared with the experimental Nakazima test and uniaxial tensile test, the predicted results show a good agreement. The parameters determined by in situ tensile test can be applied to the research of the forming limit for ductile metals.

Keywords: forming limit stress diagram; GTN model; in situ tensile test; void damage; aluminum alloy 5052-O1; sheet metal forming

1. Introduction

In sheet metal forming industry, the localized necking failure is recognized as important limitation on metal formability. For a wide range of metals, the experimental studies on forming limit have been commonly carried out. The forming limit diagrams (FLDs) have been derived from an in-plane stretching test or a hemispherical punch stretching test named Nakazima test, in which sheets are subject to biaxial stress. Although FLD has been proven to be a useful method in the analysis of formability, the experimental and theoretical studies have also shown that the maximum admissible limiting strains strongly depend on deformation modes, loading history and plastic anisotropy introduced by cold rolling\textsuperscript{11}. Kleemola and Pelkkikangas researched the forming limits of some metals which followed uniaxial and equi-biaxial pre-strain, and noticed the dependence of FLD on the magnitude and type of pre-strain. FLD has been considered to be valid for proportional loading, where the ratio between the principal stresses remains constant in a forming process\textsuperscript{2}. In fact, the forming condition is sometimes falsely equated to proportional straining. The ratio...
between principal stresses is observed to be nearly a constant during most first drawing processes in measurement and the finite element method (FEM) prediction\(^3\). A complex strain path is the main challenge in study of the forming limit. Kleemola proposed the stress-based FLD (FLSD) to avoid the effects of strain-path. FLSD, a failure criterion plotted with principal stresses, is more resistant to changes in the strain path\(^4\) and is more suitable than FLD in multi-step forming processes\(^5\) since a weak influence of the material coefficient on FLSD can be noticed. However, it is quite difficult to measure stress on a deformed panel by experiments.

Generally, during the forming test, the stresses are calculated by two methods which are incremental calculation according to the Levy-Mises flow law and FEM. Thomas, et al. reported that FLSD was derived by the transformation between strain and stress in the deformation of sheet metal\(^6\). The transformed FLSDs, which are functionally less complex than the strain-based limit, have shown that all of the apparent path-dependent effects on the forming limit vanish when properly viewed in stress coordinates. Moreover, Butuc, et al. developed a detailed study on the stress-based forming limit criterion under linear and complex strain paths\(^5\). The experimental FLSDs after proportional and non-proportional loadings for aluminum alloy (AA) 6016-T4 and back hardenable (BH) steel have proved that the forming limit stresses were overlaid in a single curve and no dependence on the strain path changes. In addition, Uthaisangsuk, et al. carried out numerical simulations with finite element (FE) program ABAQUUS to determine FLSDs. The maximum principal stresses were determined by the user-defined criterion\(^7\) and the direct current electric potential method from fracture mechanics was used to identify the characteristic Gurson-Tvergaard-Needleman (GTN) model parameters\(^8\).

As the most widely accepted model to describe the plastic behavior of porous media, GTN model was originally developed by Gurson\(^9\) and further improved by Tvergaard\(^10\) and Needleman\(^11\). The original Gurson porous plasticity theory can describe damage induced material softening, but it is not precise for the sheet metals because sheet metals usually display planar anisotropy due to cold or hot rolling processes\(^12\). In addition, the large inclusions which nucleate voids at an early stage are modeled as a distribution of “islands” of the amplitude of the void nucleation function. Thus, their size and spacing are directly specified in the analyses and a characteristic length into the formulation is introduced. The smaller second-phase particles, which require large strains for nucleation, are assumed uniform distribution\(^13\). Fortunately, extensions of this model have been proposed by several authors to include the effects of power-law viscoplasticity\(^14\) and pore anisotropy\(^12, 15-16\). However, it is still a key problem to identify the void fraction parameters involved in GTN model for a special-ized material. In this work, the modified GTN model is adopted to identify the necking initiation area and determine the maximum principal stress close to crack, and the in situ tensile test is proposed to identify parameters of GTN model. GTN model can solely serve as the failure criterion. Moreover, FLSD based on GTN model is an integration of different stress triaxility states in the process of metal deformation.

2. Constitutive Model and FE Model

2.1. Void evolution model

\[ f^* \] is a function with modified void volume fraction. When material is undamaged and incompressible, \( f^* \) equal to zero. The function of void coalescence with modified porosity \( f \) is listed as follows\(^9-11\):

\[ f^*(f) = \begin{cases} f & \text{if } f \leq f_C \\ f_C + G(f - f_C) & \text{if } f > f_C \end{cases} \quad (1) \]

\( f_0 \) denotes the original void volume fraction. Before the plastic deformation, \( f \) is equal to \( f_0 \). At higher loads, voids grow and eventually merge with the release of energy. The void coalescence takes place once the void volume fraction reaches a critical value \( f_C \). \( G \) is a constant determined by the void volume fractions \( f_0 \) and \( f_C \):

\[ G = \frac{f_0^* - f_C}{f_1 - f_C} \quad (2) \]

where \( f_0 \) is void volume fraction at the final failure of material, and \( f_0^* \) is defined as \( f_0^* = \frac{q_1 + \sqrt{q_1^2 - q_2 q_3}}{q_3} \cdot q_1 \). \( q_2, q_3 \) are the fitting parameters in GTN model, and \( q_3 \) follows the equation \( q_3 = q_1^2 \).

The evolution of void volume fraction includes two parts, the growth of the existing voids and the nucleation of new voids. The increase of void volume fraction in the model is written as

\[ \dot{f} = \dot{f}_n + \dot{f}_b \quad (3) \]

Because the matrix material is incompressible, the growth part of the existing voids \( \dot{f}_b \) is related to the hydrostatic component of plastic strain and described as

\[ \dot{f}_b = (1 - f) \varepsilon_m^p \quad (4) \]

\( \dot{f}_n \), void nucleation rate, can be induced by strain or stress, and \( \varepsilon_m^p \) represents the equivalent plastic strain. The nucleation is controlled by the plastic strain. The volume fraction of nucleation void is differentiated and expressed as

\[ \dot{f}_n = A \varepsilon_m^p + B \sigma_m \quad (5) \]

where \( A > 0 \) and \( B = 0 \).
\[ \sigma_m \text{, the hydrostatic stress, is expressed as } \sigma_m = \frac{1}{3} \sigma_{ii}, \]
in which \( \sigma_{ii} = \delta_{ij} \sigma_{ij} \) and \( \delta_{ij} \) is Kronecker delta, \( i, j = 1, 2, 3 \).

\[ A = \frac{f_s}{S_N \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left( \frac{\varepsilon_M - \varepsilon_N}{S_N} \right)^2 \right] \tag{6} \]
where \( f_s \) denotes the volume fraction of potential nucleated voids and it is the maximum of nucleation void, \( \varepsilon_N \) is the mean nucleation strain, \( S_N \) the corresponding standard deviation. The nucleation function \( A/f_s \) is assumed to have a normal distribution.

2.2. Plastic constitutive equations

The yield criterion for porous ductile sheet metals with planar anisotropy under plane stress is expressed as \[ \phi(\sigma_{ij} - \sigma_m, f) = \left( \frac{\sigma_{eq}}{\sigma_m} \right)^2 + 2q_i(f') \cosh \left( \frac{1 + 2K}{6(1 + K)} \frac{(2 + \pi)q_i \sigma_m}{\sigma_m} \right) - \left(1 + q_i(f') \right)^{\frac{2(2 + \pi)}{3}} = 0 \tag{7} \]
where \( \sigma_{eq} = (3S_0/2)^{1/2} \) represents macroscopic von Mises equivalent stress, \( i, j = 1, 2, 3 \). The deviatoric component of the Cauchy stress is calculated by \( S_{ij} = \sigma_{ij} - \delta_{ij} \sigma_m \). The average strain hardening exponent \( \bar{\pi} \) and average anisotropy parameter \( \bar{K} \) are calculated:

\[ \bar{\pi} = (n_0 + n_{40} + 2n_{45})/4 \tag{8} \]
\[ \bar{K} = (K_0 + K_{40} + 2K_{45})/4 \tag{9} \]

And \( \sigma_m \), the flow stress of matrix material, is described as \[ (1 - f^*)\sigma_M \sigma_m^0 = \sigma_y D_y^p \tag{10} \]
where \( D_y^p \) is the plastic component of macro plastic strain rate.

Under the orthogonality conditions, \( D_y^p \) is defined as \[ D_y^p = \Lambda \frac{\partial \phi}{\partial \sigma_{ij}} \tag{11} \]
where \( \Lambda \) denotes the plastic component of flow stress:

\[ A = \left( \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} + \frac{\partial \phi B}{\partial \sigma_{ij}} \delta_{ij} \right) \left( \frac{\partial \phi}{\partial \sigma_{m}} + \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} \right) \left( \frac{\partial \phi}{\partial \sigma_{m}} + \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} \right) \right] \tag{12} \]

Then Eq.(11) becomes

\[ D_y^p = \frac{\partial \phi}{\partial \sigma_{ij}} \frac{\partial \phi B}{\partial \sigma_{ij}} \sigma_{ij} \left( \frac{\partial \phi}{\partial \sigma_{m}} + \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} \right) \left( \frac{\partial \phi}{\partial \sigma_{m}} + \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} \right) \right] \tag{13} \]

where \( k, l = 1, 2, 3 \). The following two equations \[ \frac{\partial \phi}{\partial \sigma_{ij}} = \frac{3S_0}{\sigma_m} + 2q_i(f') \cosh \left( \frac{1 + 2K}{6(1 + K)} \frac{(2 + \pi)q_i \sigma_m}{\sigma_m} \right) \tag{14} \]

\[ \sinh \left( \frac{1 + 2K}{6(1 + K)} \frac{(2 + \pi)q_i \sigma_m}{\sigma_m} \right) \tag{15} \]

Assuming

\[ \alpha = \frac{(2 + \pi)q_i q_j f'}{3} \frac{1 + 2K}{6(1 + K)} \tag{16} \]

\[ \beta = \frac{(2 + \pi)q_j q_k f'}{6} \tag{17} \]

and combining Eqs.(13)-(17), the following equations are deduced:

\[ \frac{\partial \phi}{\partial \sigma_{ij}} \frac{\partial \phi B}{\partial \sigma_{ij}} \sigma_{ij} \left( \frac{\partial \phi}{\partial \sigma_{m}} + \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} \right) \left( \frac{\partial \phi}{\partial \sigma_{m}} + \frac{\partial \phi}{\partial \sigma_{ij}} \sigma_{ij} \right) \right] \tag{18} \]
\[
(1 - f') \frac{\partial \phi}{\partial t} \frac{\partial \phi}{\partial \sigma_m} + \left( \frac{\sigma_m}{\sigma_M} + 4 \frac{\partial \phi}{\partial f} \frac{\partial \phi}{\partial \sigma_M} \right) \frac{\partial \phi}{\partial \sigma_M} = \frac{2}{\sigma_M} \left[ 3 \alpha (1 - f') \frac{\partial \phi}{\partial f} + \left( \frac{\sigma_M}{\sigma_m} + 3 \alpha \frac{\partial \phi}{\partial f} \frac{\partial \phi}{\partial \sigma_M} \right) \frac{\Delta \sigma}{\sigma_M} \right] \\
(19)
\]

\[\begin{align*}
P_{ij} & = \frac{3S_{ij}}{2\sigma_m} + \alpha \delta_{ij} \\
Q_{ij} & = \frac{3S_{ij}}{2\sigma_m} + \beta \delta_{ij} \\
H & = -\frac{\sigma_M}{2} \left[ 3 \alpha (1 - f') \frac{\partial \phi}{\partial f} + \left( \frac{\sigma_M}{\sigma_m} + 3 \alpha \frac{\partial \phi}{\partial f} \frac{\partial \phi}{\partial \sigma_M} \right) \frac{\Delta \sigma}{\sigma_M} \right] \\
(22)\end{align*}\]

Combining Eq.(13) and Eqs.(20)-(22) into one equation, \( D_i^p \) can be written as

\[D_i^p = \frac{P_{ij}Q_{kl}\sigma_{kl}}{H} \]

(23)

The elastic component of deformation tensor can be described as

\[D_i^e = \frac{1 + \nu}{E} \sigma_{ij} - \frac{\nu}{E} \delta_{ij} \sigma_m \]

(24)

where \( E \) is the elastic modulus, \( \nu \) the Poisson’s ratio.

From Eqs.(23)-(24), the GTN-based plastic constitutive relation is concluded as follows:

\[D_i = D_i^p + D_i^e = \frac{1 + \nu}{E} \sigma_{ij} - \frac{\nu}{E} \delta_{ij} \sigma_m + \frac{1}{H} P_{ij} Q_{kl} \sigma_{kl} \]

(25)

2.3. Description of FE model

The numerical Nakazima test is invited to calculate the stresses and construct FLSD. Fig.1 shows FE model of Nakazima test. The diameter of the punch is 100 mm. Since material failure always develops on the free material surface, the sheet metal geometry is also meshed in three element layers (top layer, middle layer and bottom layer) with three bias ratios, shown in Fig.1. The development of the stresses in one element in the top layer, which is in contact with the punch, is quite unsteady. The stresses in the element at the same location but at the bottom of the sheet surface show much more stable course. Therefore, the analyses of the plastic deformations and the stresses are performed exclusively in the element layer on the side to the free surface\(^\text{[7]}\). The problem that the stresses can be influenced by the contact situation between punch and specimen is avoided.

Fig.1  Finite element model of Nakazima test.

The contacts between the sheet, the rigid punch and the die are modeled with the surface-to-surface contact pair. Coulomb’s coefficient of friction between all of the tool surfaces and the blank sheet is set at \( \mu = 0.1 \text{[21]} \).

The width of sample gradually increases from 10 mm to 180 mm, and the shape and some important dimensions are listed in Fig.2.

Fig.2  Shapes and dimensions of specimens for Nakazima test.
The analysis is divided into four steps. In the first step, for avoiding the chattering before contact, the vertical displacement of sheet is fixed and this boundary condition is applied to the reference point of sheet. In the second step the holder die is pushed onto the sheet to establish contact. In the third step the holding force is applied to the die. Finally, the boundary condition of fixed sheet is removed and replaced by the force on the punch. The planar anisotropic constitutive equations are implemented in ABAQUS with a user defined VUMAT routine[22-24] and the principal item of the GTN-model is a yield potential.

3. Experimental Material and Methods

3.1. Material properties

The material of sheet 1.0 mm in thickness is AA 5052-O1. The chemical composition of AA5052-O1 is given in Table 1. The mechanical properties are listed in Table 2.

| Table 1 Chemical composition of AA5052-O1 wt% |
| Mg | Cu | Mn | Si | Fe | Al |
| 2.27 | 0.14 | 0.32 | 0.51 | 0.31 | Balance |
| Cr | Ni | Zn | Ti | Na |
| 0.27 | 0.24 | 0.04 | 0.05 | <0.01 |

| Table 2 Mechanical properties of AA5052-O1 |
| E/GPa | \sigma_V/MPa | \sigma_f/MPa | K_0 | K_1 | K_3 |
| 75 | 825 | 623 | 401.67 | 440.29 | 411.92 |
| K | n_0 | n_0 | n_0 | n_0 |
| 424 | 0.269 | 0.298 | 0.253 | 0.28 |

3.2. Determining GTN model parameters with in situ tensile tests in SEM

The material of sheet 1.0 mm in thickness is AA5052-O1. According to the plastic constitutive equation mentioned in the last section, nine coefficients require to be identified in GTN model: \( f_0, f_c, f_n, f_s, \theta_0, S_0, q_1, q_2, q_3 \). The void volume fractions \( f_0, f_c, f_n, f_s \) are described by the void surface proportions and determined by Image-Pro plus software of the scanning electron microscope (SEM) microstructures.

Since the single edge notch is likely to invite stress concentration and change the triaxial stress state, the smooth sample is chosen to avoid the micro cracks around the notch. Small flat tensile test pieces (40 mm×12 mm), 1 mm in thickness with the gauge length being 20 mm, are prepared. The shape and dimensions are given in Fig.3. The void evolution is observed by in situ test at the original point, designated as \( O \) on the sample. The loading direction is along \( X \) axis.

The in situ tensile tests in SEM are performed in a JSM 5800 SEM equipped with a JEOL tensile stage at a strain rate of 1.0 mm/min at room temperature.

4. Results and Discussion

The mechanism of ductile fracture is described as a damage accumulation process and there are three stages in the development of ductile fracture known as void nucleation, growth and coalescence. The load-displacement curve obtained from in situ tensile test is shown in Fig.4. The corresponding locations for determining the void fraction are also presented.

4.1. GTN model parameters

(1) The first stage concerns the nucleation of micro-voids in the inclusions. The primary void comes from few original voids and the secondary phase particles, shown in Fig.5. The original void, \( f_0 \), is counted as 0.002978. The average size of secondary phase particles is 2.674 \( \mu \)m. Through in situ observation, the
noticeable decohesion and deformation in voids and particles are observed at the displacement 0.36 mm in which the plastic strain is 0.102 8. For non-linear shape, strains are calculated by integral method and $\Delta l$ obeys circular function along the grip length.

Fig.6 displays the growth of voids at different loads, which reveal that the voids initiate in the interface for smaller inclusions and in the interior for bigger particles. When displacement is more than 0.36 mm, micro-void forms for crack and decohesion, shown in Fig.6(a). $f_N$ denotes the potential nucleated volume fraction that includes the nucleated fraction of second-phase particles (0.014 573, see Fig.5) and the secondary void nucleated fraction, presented in the fractograph. Due to chronological sequence, the volume of the secondary void is smaller than the primary void. Furthermore, for the stress concentration, the secondary voids generally occur around the primary voids and distribute in a cluster.

Fig.6  Growth of voids at different loads.

Accordingly, the secondary voids are discriminated by Image-Pro plus software in a view field. With development of magnification, discrimination capacity is enhanced but the smaller void area can be identified. The magnification has little influence on the results since $f_N$ is the ratio. Considering the growth of the secondary void, the minimum area of the secondary void is selected as the sample of the secondary void. The amount of the secondary void is 143. The volume fraction of the secondary void is obtained as 0.010 328. Two parts of void fraction, 0.014 573 and 0.010 328, are added up and 0.024 9 is assigned to $f_N$. It is assumed that $\delta_N$ is equal to 0.102 8 at the moment when the distinct crack and debonding in the second-phase particle are observed.

(2) The second stage corresponds to the extensional and dilatational growth of micro-voids. The voids propagate directly along the crack of the damaged inclusion with higher load. When load increases to about 700 N, the displacement reaches 1.12 mm and void fraction develops to 0.030 103, micro-crack initiates and the material bearing capacity loses quickly as some connected void bands form. Similarly, $f_C$ is identified by area ratio and equal to 0.030 103. Significant changes could be noticed that the dimensions of micro-voids are clearly larger and deeper at 1.12 mm displacement as shown in Fig.6(b). The clustered inclusions are potentially easier to be damaged than single inclusion because the interactions among inclusions will enhance local matrix strain and increase initial crack size for propagation.

(3) The third step consists of the coalescence by the tearing of the ligaments between enlarged voids. In the final stage of the fracture, micro-voids are interconnected by a fast rupture perpendicular to the tensile loading. When displacement reaches 1.80 mm, complete separation (fracture) occurs and the macroscopic stress carrying capacity loses completely. The void volume fraction $f_f$ is evaluated as 0.048 54 from the fractograph (see Fig.7).

Fig.7  Fractograph of AA5052-O1.

Finally, the value of 0.1 is assigned to $S_N^{(9)}$. To reflect the interaction in two void groups in GTN model, $q_1$, $q_2$, $q_3$ are quantified as 1.5, 1, 2.25, respectively$^{(25)}$.

4.2. Uniaxial tensile test

Uniaxial tensile of thick plate is a common test to estimate the ductility of materials. The experiment and theoretical study are carried out for uniaxial tensile of AA5052-O1 1 mm in thickness. The shape and dimensions on standard specimen are shown in Fig.8. The uniaxial tensile tests are carried out on the tensile test machine. The uniaxial tensile simulations are carried out in ABAQUS servers.
The experimental fracture sheets are presented in Fig.9. Fig.10 shows the contour of the simulated stress distribution. The stresses in cracked parts return to zero. Compared with the test, the necking zone departs from the middle of the specimen due to anisotropy. The necking zone in simulated results has a good agreement with the experimental results.

4.3. FLSD of AA5052-O1

Based on the identified GTN model parameters, the Nakazima tests are simulated with the increase of width from 10 mm to 180 mm. The stress states before and after fracture in sheet of the width of 100 mm are shown in Fig.11. Three critical elements located in necking zone at bottom layer in one sample are chosen at the last loading step without the appearance of crack elements, and the stress difference between every two elements is within 10%. The mean values of principal stresses among three elements, shown in Fig.11(a), are calculated and regarded as the critical principal stress for one sample. FLSD is plotted according to the critical maximal principal stress $\sigma_1$ versus the critical middle principal stress $\sigma_2$ before crack on all widths, shown in Fig.12.

4.4. Limit diagram based on strain

The classical FLD is applied to validating the numerical model and the proposed approach in this work. The experimental Nakazima tests are respectively conducted with the widths of 60, 80, 100, 120 mm, shown in Fig.13, at room temperature, the limit strains are obtained from the experimental Nakazima tests. Based on the numerical results in Section 4.3, the mean values of principal strains among three elements are calculated and assigned to the corresponding sample as the critical principal strain. Comparison between numerical and experimental forming limit diagrams based on strain is conducted and depicted in Fig.14, where $\epsilon_1$ denotes the critical maximal principal strain,
the critical principal strain. The left hand side of FLD is tension-compression region, and the right hand side of FLD is tension-tension region. The samples with the widths of 60, 80, 100 mm locate in the left region of Fig.14 and the sample with the width of 120 mm locates in right region of Fig.14. Due to the parameters determined by the in situ tensile test, the numerical FLD is in an agreement with the experimental results.

![Fig.13](image1.png) Nakazima tests for part of specimens.

![Fig.14](image2.png) Comparison of FLDs of AA5052-O1 between numerical and experimental results.

5. Conclusions

(1) The parameters in GTN model are identified by the in situ tensile tests. Combining the load-displacement curve with the microstructure of tensile surface, the damage evolution of AA5052-O1 is described in three phases (void initiation, growth and coalescence) and the GTN model parameters are derived from counting void fractions at various damage stages. According to the experimental results, \( f_0\), \( f_N\), \( f_C\), \( f_r\) are assigned as 0.002 918, 0.024 9, 0.030 103, 0.048 54, respectively. Through simulation study and experimental verification, the GTN model parameters obtained from test are proved available for ductile metals and the failure criterion of sheet metal based on micro-void evolution mechanism is reliable.

(2) The in situ tensile test is a helpful method to identify the GTN model parameters and further explore the micro-scale mechanism of void evolution. The method, i.e., the FEM analysis cooperating with the GTN model parameters determined by testing, is suggested to research the forming limit stress diagram on the premise that FLSD is independent on strain path. GTN model can solely serve as the failure criterion. Moreover, FLSD is more conveniently and widely used for many parts and multi-loading routes, for FLSD is a merger of different stress triaxial states. This technique is also helpful for die designer to adjust the processing parameters such as draw bead flow stresses and binder pressure according to FLSD. More accurate prediction of the forming limit further depends on the development of damage model.

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