Analysis of Forming Limit of Sheet Metals Considering Vertex Localized Necking and Ductile Damage Criterion

Farid Hosseini Mansoub[1], Ali Basti [2*], Abolfazl Darvizeh [2], Asghar Zajkani [3]
[1] Mechanical Faculty, University Campus 2, University of Guilan, Rasht, Iran, hosseinimansoubfarid@gmail.com
[2] Mechanical Faculty, University of Guilan, Rasht, Iran, basti@guilan.ac.ir
[2] Mechanical Faculty, University of Guilan, Rasht, Iran, adarvizeh@guilan.ac.ir
[3] Mechanical Faculty, Imam Khomeini International University, Qazvin, Iran, zajkani@eng.ikiu.ac.ir

Abstract

In the present paper, a predictive strain-rate-dependent model of localized necking is developed by using a modified Vertex theory. A novel ductile damage -based criterion is proposed to control the necking parameters including on stress triaxiality, strain hardening exponent and Lode parameters. As a characterization parameter, elastic modulus is eventually chosen to measure the ductile damage during process of plastic deforming. Furthermore, a vectorized user - defined material subroutine is developed to finite element simulation by ABAQUS software, according to original formulations, in order to create linkage between related essential models. A typical strain rate-dependent metal is selected to validate the modified Vertex theory. To examine the accuracy of the results from present simulated study, the applicability is considered to compare with the experimental results. Tests of forming are also performed for steel 13 and steel 14 sheets to measure forming limit diagram. It should be noted that the simulated forming limit diagrams are in good agreement with the experimental data. However, this correlation at low strain rates is better than high strain rates. However, this increase will be infinitesimal for the lower strain rates as compared to the higher ones.

Keywords

Ductile damage; Stress state; Strain rate; Forming limit diagrams; Vertex theory.

*Corresponding Author: Email: basti@guilan.ac.ir

1. Introduction

The present paper gives an efficient method based on the Vertex theory in localized necking in order to determine forming limit diagrams (FLDs), including strain rate dependences. Besides, introducing an accurate damage function based on simple continuum damage mechanics (CDM), the model is related to the stress state (Triaxiality and Lode parameters). To examine the accuracy of the results from the present simulation and compare with the experimental results, applicability is considered. Forming limit tests are also performed for St 13 and St14 sheets to measure the FLD. It is worthy to mention that all these concerns have not been considered simultaneously in the previous studies.

2. Ductile Damage Controller Model

The elasticity modulus will decrease the plastic deforming and this will be due to the accumulation of damage in the material.

$$E_D = E_0 e^{-p\varepsilon} \tag{1}$$

$$D = 1 - \frac{E_D}{E_0} = 1 - e^{-p\varepsilon} \tag{2}$$

The damage function R is defined as follows:

$$R = \frac{D_i}{D_c} \tag{3}$$

The value of R is determined between zero (undamaged) and one (fracture). D_c is the critical value of the ductile damage.

$$D_c = f(\eta, \bar{\theta})(1 - e^{-p\varepsilon_f}) \tag{4}$$

Where η is the triaxiality and $\bar{\theta}$ is the Lode angle. Also, ε_f is the fracture strain calculated through $\varepsilon_f = n^p e^{(p/2)}$ as $p = 1$ and $p = 9(1-\vartheta)/4$ represent a true and nominal fracture strains, respectively. The value of p is relevant to the strain-hardening exponent in plastic deforming of materials [1].

$$f(\eta, \bar{\theta}) = 0.58\sinh(1.5\eta) - 0.008\bar{\theta}\cosh(1.5\eta) \tag{5}$$

$$\Delta D_i = f_i(\eta, \bar{\theta})\, p e^{-p\varepsilon_i} \Delta\varepsilon_i \tag{5}$$

$$D_i = D_{i-1} + \Delta D_i \tag{6}$$

All equations are compiled through a User-defined material subroutine as exported to Abaqus package for the mechanical behavior.

3. Vertex Localized Predictor Model

According to the studies conducted by Jie et al. [2] on the limit strain based on the Vertex theory and considering the strain exponent equation, the equivalent strain and the strain rate as $\bar{\sigma} = k\bar{\varepsilon}^n \dot{\bar{\varepsilon}}^m$ will give:

- On the left side of the FLD curve:

$$\varepsilon_1 = \frac{m+n}{1+\beta} + \frac{\sqrt{3}(m+n)s(\bar{\sigma}, \bar{\varepsilon})}{2\sqrt{1+\beta+\beta^2}} \tag{8}$$

- On the right side of the FLD curve:

$$\varepsilon_1 = \frac{3\beta^2 + (m+n)(2+\beta)^2}{2(2+\beta)(1+\beta+\beta^2)} + \frac{(m+n)s(\bar{\sigma}, \bar{\varepsilon})}{2(2+\beta)\sqrt{1+\beta+\beta^2}} \times [(2+\beta)\sqrt{3(1+\beta+\beta^2)\bar{\varepsilon}} - 3\beta^2)] \tag{9}$$

Where n is the stiffness strain value, m is the exponent of sensitivity to strain rate, and k is the stiffness coefficient calculated via uniaxial tests. β is the ratio of minor strain to major strain during the loading process and $s(\bar{\sigma}, \bar{\varepsilon}) = -c\bar{\sigma} / \bar{\varepsilon}^{\frac{n}{m+1}}$ in which $\bar{\varepsilon}$ and $\bar{\sigma}$ are an equivalent strain, equivalent stress of the Von Mises and c is an integration constant, which can be determined from the uniaxial test at various strain rates. These values reveal final strain for sheet metals relevant to strain rate and considering localized necking based on the Vertex theory.

4. Numerical model in ABAQUS application

All the specimens (based on the standard of ASTM E2218) were simulated using commercially available finite element code ABAQUS/Explicit.

Physical properties like density, elastic properties like Young's modulus and Poisson's ratio, plastic properties and damage criteria are all put into the application in the form of data "Table 1".

Table 1. The mechanical and constants values properties of St 13 and St14 steel sheets [1-3]

Materials	Elasticity modulus (GPa)	Density (g/mm³)	Yield stress (MPa)	ϑ	m	n	k (MPa)	c (MPa^{-1})
St13	180	7.85	250	0.3	0.0191	0.2387	650	-5×10^{-5}
St14	210	7.85	300	0.3	0.0187	0.23	524.58	-5×10^{-5}

It is, however, worth mentioning that, according to Eq. **Error! Reference source not found.**, the critical damage values are calculated to be 0.1387 and 0.1374 for ST 13and St14 respectively. The sheet is divided into meshes with R3D4 and C3D8R elements. The factor 1000 is selected for the mass scaling option. Sizes of the meshes are considered 1 mm, and the thickness of the sheet is also 1 mm. It is suggested that the minimum length of element should be higher than the shell thickness, based on the mesh sensitivity study [1]. The constitutive relation, yield criteria and ductile damage criteria of this material were compiled in user material subroutine (UMAT) of ABAQUS. And according to the formulations proposed above, the UMAT subroutine in the finite element application of the ABAQUS is used to analyze the model, including 10 variables. For instance, SDV1 is defined as the damage value. When the damage value reaches the unit, the analysis stops. Other parameters like the plastic strain, Von Mises stress and the strain rate are noted and picked up to input into the Vertex equations to draw the forming limit diagrams. Then they are classified based on strain rate to obtain FLDs in distinctive strain rate.

5. Experimental procedures

In order to acquire major and minor strains limits, from plane Nakazima test, a hemispherical punch has been conducted. The punch-stretch apparatus and sheet metal specimens were all prepared based on the standard. The marks of circle on the blank specimen have been electrochemically etched. To generate different strain rate we change loading velocity. According Eq. **Error! Reference source not found.**) we able to calculate strain rate.

$$\dot{\varepsilon} = \frac{w_0 v_0}{3\sqrt{2}R_s^{\,2}} \times 100 \qquad (10)$$

Where v_0 is the loading velocity, w_0 is the maximum deflection of the plate and R_s is the diameter of hemispherical punch.

Major and minor strains ($\varepsilon_1, \varepsilon_2$) with an initial length (l_0) of 2.5 mm can be calculated through following equations:

$$\varepsilon_i = \frac{l_1 - l_0}{l_0} \times 100 \qquad (7)$$

where l is the maximum or minimum deformed length of the circle diameter.

Deforming the specimen to the point of necking is desirable. This could be achieved by stopping the movement of press ram. When the force in the force-displacement curve begins to drop.

6. Discussion and Results

To examine the accuracy of results of the present study and compare with the experimental results; applicability is considered. It should be noted that the rule for these simulated FLDs is in good agreement with the experimental points.

The levels of the FLDs grow up upon the strain rate increases. This effect is still negligible in the low (static) strains.

7. Conclusions

This paper gives an efficient method based on the Vertex theory to determine FLDs including strain rate calculations. Besides, introducing a damage function based on a simple continuum damage mechanics (CDM) is dependent on stress state (Triaxiality and Lode parameters). In the application of the ABAQUS for a finite element simulation, a UMAT subroutine is established for the computation of major and minor strains, considering above concepts which enable the model to evaluate initiation of the instability and obtain FLDs in a phenomenological way. The model will determine an element when it has reached the critical point of failure. When the damage value reaches the unit, the analysis stops until each component with its damage value reaches the critical point. In this state, other parameters like major strain, minor strain, the Von - Mises stress and strain rate are noted and picked up to be put into Vertex equations to draw forming limit diagrams and then they are classified based on strain rate to obtain FLDs in distinctive strain rate.

It is worthy to mention that all these concerns have not been considered simultaneously in previous studies. Applicability is considered in order to examine the accuracy of the results from the present study and compare with the experimental results. It should be noted that rule of these simulated FLDs is in good agreement with the experimental points. However, this correlation at low strain rates is better than high strain rates. Furthermore, the level of FLDs goes up as strain rate increases; yet, this effect is negligible in low (static) strain rates and is more observed in higher strain rates in FLDs.

8. References

[1] X. Ma, F. Li, J. Li, Q. Wang, Z. Yuan, Y .Fang, Analysis of forming limits based on a new ductile damage criterion in St14 steel sheets, 2015.
[2] M. Jie, Generalized criteria for localized necking in sheet metal forming, 2003.
[3] M. Saradar, A. Basti, M. Zaeimi, Numerical study of the effect of strain rate on damage prediction by dynamic forming limit diagram in high velocity sheet metal forming, Modares

Mechanical Engineering, 14(16) (2015). (in persian)