Investigation on tensile deformation and failure for 5052 aluminum alloy based on continuum damage model

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Abstract: A VUMAT user material subroutine for the Lemaitre continuous damage mechanics model was developed based on the finite element solver ABAQUS /Explicit platform to investigate the deformation and failure behavior of 5052 aluminum alloy. The mechanical property parameters and damage parameters of 5052 aluminum alloy were identified by the inversion method combining tensile test and finite element simulation. The numerical simulation results showed that the force-displacement curves predicted by the established damage model were in good agreement with the experimental measurement, and the fracture location was close to the experimental results, which verified the accuracy and effectiveness of the damage parameters. The growth and distribution law of damage variable could be intuitively represented by the simulation results by the Lemaitre damage model.

1. Introduction
In recent years, automobile lightweight has become one of the main trends in the development of automobile industry. Aluminum alloy has the advantages of light weight, high strength and good corrosion resistance, and has been widely applied in automobile, aircraft, high-speed railway and ship manufacturing industries [1]. However, aluminum alloy is prone to fracture, wrinkle, springback and other forming defects in the forming process [2]. Therefore, it is of great significance to accurately predict the damage failure behavior of aluminum alloy under large deformation conditions.

As a constitutive model based on the damage variable, the Lemaitre continuous damage model [3] can accurately describe the damage and fracture behavior of metallic materials, and has important scientific significance and engineering value. Lemaitre damage model has been investigated extensively by many scholars. For instance, Hambli [4] obtained the damage parameters from the tensile test and performed numerical analysis on the metallic sheet through the finite element method, which showed that the Lemaitre model could better simulate the crack propagation path than the microscopic damage mechanics model. Bonora et al. [5] proposed a material subroutine based on a continuous damage mechanics model, and successfully identified the damage parameters of 20MnMoNi55 steel through
tensile tests of circular notched specimens. Keshavarz et al. [6] developed a Lemaitre damage model subroutine coupled with anisotropy plasticity to simulate and analyze the yield behavior and crack generation mechanism of API5L X100 pipeline steel. Aghaei et al. [7] adopted a Lemaitre model combining with combined hardening to study micromechanical behavior of DP600 steel under tensile loading.

In this study, taking 5052 aluminum alloy as the research object, the Lemaitre damage model was developed and embedded into the ABAQUS/Explicit platform by programming a VUMAT material subroutine. The mechanical property parameters and damage parameters of 5052 aluminum alloy sheet were determined by the inversion method combining tensile test and finite element simulation. The accuracy and effectiveness of the damage parameters were verified by comparing the prediction results by the Lemaitre model with the experimental results, which provided a valuable reference for the damage evolution analysis of the deformation process for aluminum alloy sheet in the future.

2. Lemaitre damage model

2.1. Lemaitre continuous damage theory

In order to study the isotropic damage behavior of ductile metallic materials, Lemaitre et al. [3] proposed a thermodynamically coupled continuous damage identification method, which considered the effect of the damage process on the equivalent stress of material, and could directly give the damage evolution law of the material according to the variation of macroscopic properties during the deformation process.

The damage increment \( \Delta D \) of Lemaitre damage model to describe the severe deformation behavior of materials is expressed as follows

\[
\Delta D = \frac{D_C}{\varepsilon_R - \varepsilon_D} \left[ \frac{2}{3} (1 + v) + 3(1 - 2v) \left( \frac{\sigma_H}{\bar{\sigma}} \right) \right] \cdot (\bar{\varepsilon}_p)^2 \cdot \Delta \bar{\varepsilon}_p
\]

where \( D_C \), \( \varepsilon_D \), and \( \varepsilon_R \) are the three damage parameters of Lemaitre model. \( D_C \) is critical fracture damage value, \( \varepsilon_D \) is the strain value at initial damage, and \( \varepsilon_R \) is the strain value at fracture. \( \bar{\sigma} \) and \( \sigma_H \) are Von Mises equivalent stress and mean stress, respectively. \( \bar{\varepsilon}_p \) and \( \Delta \bar{\varepsilon}_p \) are equivalent plastic strain and its increment, respectively.

2.2. Implementation of numerical algorithm

The whole process of material deformation is divided into two stages: elastic deformation and plastic deformation [8]. In the secondary development of the VUMAT subroutine [9] for Lemaitre damage model, it is necessary to determine the elastic and plastic deformation stages and update the state variables. The specific process is as follows.

1) Elastic deformation stage: assuming only elastic strain, plastic strain increment \( \Delta \bar{\varepsilon}_p = 0 \). After replacing the stress in the yield criterion with the trial stress tensor \( S^{trial} \), the yield condition \( \phi(S) \leq 0 \), indicating that the material is still in the elastic stage. Variables at \( t_{i+1} \) are updated as follows

\[
\sigma_{i+1} = \sigma^{trial}
\]

\[
\bar{\varepsilon}_p^{i+1} = \bar{\varepsilon}_p^i
\]

\[
D_{i+1} = D_i
\]
2) Plastic deformation stage: the yield condition $\Phi(S) > 0$ is obtained after $S_{\text{trial}}$ is substituted for the stress in the yield criterion, which indicates that the material enters the plastic deformation stage. Therefore, the yield surface needs to be expanded at $\Delta t$ to satisfy the consistency condition. The plasticity factor $\Delta \gamma$ will be determined by the return mapping method and used to update the state variables whenever plastic deformation occurs. The plasticity factor $\Delta \gamma$ is solved at $t_{i+1}$, and the next stress, strain and damage values are updated as follows

$$\sigma_{i+1} = \sigma_{\text{trial}} - 2\mu\left(1 - D_i\right)\Delta \gamma q$$

and

$$\bar{\epsilon}_{i+1}^p = \bar{\epsilon}_i^p + \frac{2}{3}\Delta \gamma$$

where $q$ is the unit normal vector of yield surface.

According to the numerical algorithm mentioned above, the state variables in the elastoplastic stage are updated, and the VUMAT user subroutine for Lemaitre damage model is programmed according to the authors' previous research [10]. The damage parameters of material are obtained by the finite element inversion method, and the material subroutine is verified by the tensile test.

3. Experiment and simulation

3.1. Tensile test

The experimental material is the commercial 5052 aluminum alloy sheet, and its main chemical composition is shown in Table 1. The gauge length of tensile specimen of aluminum alloy sheet is 50 mm, and the thickness is 3 mm.

In order to investigate the damage evolution process of 5052 aluminum alloy, tensile tests were carried out at room temperature at a constant rate of 1 mm/min until the specimens were completely fractured. Fig. 1 shows the true stress versus true strain curve obtained from the uniaxial tensile experiment. It can be seen that the tensile specimen of aluminum alloy begins to yield and plastic deformation occurs when the stress is 84.7 MPa.

Table 1 Chemical compositions of the 5052 aluminium alloy (wt. %)

| Element | Mg  | Si  | Mn  | Cr  | Ni  | Fe  | Cu  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Value   | 2.46| 0.06| 0.25| 0.19| 0.22| 0.27| 0.04| Balance |

![Fig. 1 True stress versus true strain curve of 5052 Al alloy specimen](image)

The Hollomon equation, Swift equation and Voce equation are three most commonly used constitutive equations after materials yielding. These expressions can be described as follows

Hollomon equation: $\sigma = K_H \bar{\epsilon}_p^{n_H}$

(7)
Swift equation:

\[ \sigma = K_S \left( \varepsilon_p + \varepsilon_0 \right)^{n_S} \]  

Voce equation:

\[ \sigma = \sigma_s - K_V \exp \left( -n_v \varepsilon_p \right) \]  

where \( K_H, K_S \) and \( K_V \) are three hardening parameters. \( n_H \) and \( n_S \) are the strain hardening exponents, respectively. \( n_V, \varepsilon_0, \varepsilon_p \) and \( \sigma_s \) are the stress saturation rate, initial strain, true plastic strain, and saturation stress, respectively.

Hollomon constitutive equation can be regarded as a special case of Swift equation. Since Swift equation is appropriate for describing the strain hardening behavior of ductile metallic materials in the deformation stage, while Voce equation can describe the stress saturation behavior in the late deformation stage. According to the tensile test results, the unsaturated Swift equation and saturated Voce equation are adopted to describe the plastic behavior of the material in the deformation stage by linear weighting. The constructed constitutive model can be expressed as:

\[ \sigma = a \left[ K_S \left( \varepsilon_p + \varepsilon_0 \right)^{n_S} \right] + \left( 1 - a \right) \left[ \sigma_s - K_V \exp \left( -n_v \varepsilon_p \right) \right] \]  

where \( a \) is a weighted coefficient, which is identified by iterative optimization algorithm.

The coefficients of Hollomon and Voce constitutive equations are obtained by fitting the true stress-strain curves of tensile specimen. After simulation simulation and error analysis, the weighted coefficient \( a \) is determined to be 0.46. Table 2 summarizes the final mechanical property parameters of 5052 aluminum alloy.

| Parameter | \( \varepsilon_0 \) | \( a \) | \( n_v \) | \( n_S \) | \( K_S /\text{MPa} \) | \( K_V /\text{MPa} \) | \( \sigma_s /\text{MPa} \) |
|-----------|-----------------|-------|--------|--------|-----------------|-----------------|-----------------|
| Value     | 0               | 0.46  | 26     | 0.22   | 335             | 130             | 208             |

3.2. Finite element modelling

Finite element modeling was carried out according to the actual physical dimension of tensile specimen. The boundary and load conditions were consistent with the actual tensile test. The three-dimensional eight-node solid element with reduction integral (namely C3D8R element) was adopted. The mesh density in the center deformation region is refined to improve the accuracy of the solution. The finite element model and refining mesh of the tensile process are shown in Fig. 2.

By the inversion method of comparing the true stress-strain curves between tensile test and numerical simulation, the maximum true strain in the deformation region of specimen at fracture was obtained, which was the critical value of ductile fracture criterion \( \varepsilon_R = 0.12 \). The critical damage \( D_C = 0.64 \) and the damage model parameter \( \varepsilon_D = 0.05 \) were determined by linear fitting equation.

Fig. 2 The finite element model and refining mesh of the tensile process.

4. Results and discussion
The tensile test process was simulated based on the ABAQUS/Explicit solver, and then the tensile force versus displacement curve, damage distribution and fracture location were predicted by the established Lemaitre damage model.

Fig. 3 shows the comparison of tensile force versus displacement curve between the Lemaitre model simulation and the experimental result. It could be found that the simulated fracture load and fracture displacement were 5586.7N and 5.93mm respectively, which was very close to the measured fracture load of 5893.1N and the fracture displacement of 5.79mm. The relative errors were only 5.48% and 2.36%, respectively.

Fig. 3 Comparative results of load-displacement curves obtained by finite element simulation and tensile test.

Fig. 4 shows the comparison between the distribution of damage variable at crack initiation simulated by Lemaitre damage model and the fractured specimen of aluminum alloy. It was observed that fracture location was close to the experimental result. The damage amount of the elements in the central region of tensile specimen reached its critical damage value when the tensile displacement was 5.9 mm, and the crack propagated along the direction perpendicular to the loading force, which was consistent with the experimental result.

Fig. 4 Damage distribution predicted by Lemaitre damage model and fracture specimen of aluminum alloy.

Given the above, the VUMAT subroutine based on Lemaitre damage model algorithm could predict the force-displacement curve and fracture position of the tensile specimen with high accuracy after coupling the damage parameters obtained from experimental data, which also proved the effectiveness and accuracy of the constructed material subroutine and damage parameters. Furthermore, the Lemaitre damage model could directly output the distribution results of damage variable, which was of greater guiding significance to the prediction of damage and fracture behavior compared with traditional von Mises model.
5. Conclusion

The main conclusions of this study are summarized as follows.

The VUMAT material subroutine of Lemaitre damage model for 5052 aluminum alloy was developed by means of the finite element solver ABAQUS/Explicit platform.

Tensile tests were carried out on standard specimen of 5052 aluminum alloy at room temperature. The damage parameters of the Lemaitre model were identified by the finite element inversion method.

The validity of VUMAT subroutine and damage parameters was verified by tensile tests. The comparative results between numerical simulation and tensile test showed that the Lemaitre damage model had a high prediction accuracy for the stress-strain curve, forge-displacement curve and fracture position, and could output the obtained damage variable directly.

Acknowledgments

The authors appreciate the financial support for the present research from the National Natural Science Foundation of China (No. 11772013), the China Postdoctoral Science Foundation (No. 2019M650659) and the State Key Laboratory of Acoustics (Chinese Academy of Sciences).

References

[1] Tisza M, Czinege I. Comparative study of the application of steels and aluminium in lightweight production of automotive parts[J]. International Journal of Lightweight Materials and Manufacture, 2018, 1(4): 229-238.

[2] Li H, Yao X, Yan S, et al. Analysis of forming defects in electromagnetic incremental forming of a large-size thin-walled ellipsoid surface part of aluminum alloy[J]. Journal of Materials Processing Technology, 2018, 255: 703-715.

[3] Lemaitre J, Desmorat R, Sauzay M. Anisotropic damage law of evolution[J]. European Journal of Mechanics, 2000, 19(2):187-208.

[4] Hambli R. Comparison between Lemaitre and Gurson damage models in crack growth simulation during blanking process[J]. International Journal of Mechanical Sciences, 2001, 43(12): 2769-2790.

[5] Bonora N, Gentile D, Pirondi A. Identification of the parameters of a non-linear continuum damage mechanics model for ductile failure in metals[J]. The Journal of Strain Analysis for Engineering Design, 2004, 39(6): 639-651.

[6] Keshavarz A, Ghajar R. Effect of isotropic and anisotropic damage and plasticity on ductile crack initiation[J]. International Journal of Damage Mechanics, 2019, 28(6): 918-942.

[7] Aghaei M, Ziaei-Rad S. A micro mechanical study on DP600 steel under tensile loading using Lemaitre damage model coupled with combined hardening[J]. Materials Science and Engineering: A, 2020, 772: 138774.

[8] Zhao P, Chen Z, Dong C. Investigation and prediction of tearing failure during extrusion based on a modified shear damage model[J]. Mechanics of Materials, 2017, 112: 28-39.

[9] Zhao P J, Chen Z H, Dong C F. Failure analysis based on microvoids damage model for DP600 steel on in-situ tensile tests[J]. Engineering fracture mechanics, 2016, 154: 152-168.

[10] Zhao P J, Chen Z H, Dong C F. Failure analysis of warm stamping of magnesium alloy sheet based on an anisotropic damage model[J]. Journal of materials engineering and performance, 2014, 23(11): 4032-4041.