Rare Metal Materials and Engineering
Volume 52, Issue 6, June 2023
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Gui Hailian, Zhang Chen, Liu Hao, et al. An Improved Lemaitre Fracture Criterion and Its Application to Crack Prediction in Bending Forming[J]. Rare Metal Materials and Engineering, 2023, 52(06): 2031-2038.

ARTICLE

An Improved Lemaitre Fracture Criterion and Its Application to Crack Prediction in Bending Forming

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Abstract: In order to predict the crack defects in sheet metal bending, an Lemaitre criterion was improved to effectively predict the forming limit in bending while considering the stress triaxiality $\delta_m/\bar{\delta}$, the maximum principal stress ratio $\delta_1/\bar{\delta}$, and the influence of plastic strain on the damage. Taking 7075-T6 aluminum alloy as the research object, the crack forming in sheet bending was simulated to obtain the criterion parameter so as to determine the cracking threshold. Three point bending test and metallographic test were carried out on 7075-T6 aluminum alloy sheet with 6 mm in thickness. The accuracy of the criterion for crack prediction was verified by comparing the press measure of experimental, simulation and theoretical values. The results show that the improved Lemaitre fracture criterion is 9.7 mm, which is consistent with the results of simulation and experiment. Therefore the improved Lemaitre fracture criterion has a certain accuracy in predicting the crack of bending forming.

Key words: ductile fracture; Lemaitre criterion; crack prediction; 7075-T6 aluminum alloy

In recent years, the plastic forming methods are continuously evolving; in the process of new product development, if the blank, die, forming conditions of the process parameters are not properly selected, products often generate cracks and other defects, which cannot meet the quality requirements, resulting in large economic losses. Traditional plastic forming process and die design use trial and error method and empirical method, by which product design and manufacturing cost is high and cycle is long. Therefore, many scholars have devoted themselves to study the theory and method of process formability evaluation for defect prediction. With the development of technology, the application of finite element and boundary element[1–3] numerical methods in plastic forming analysis has become a hot topic. However, only the stress and strain of plastic forming can be analyzed, and the information whether cracks will occur cannot be given.

A lot of research have been done on the prediction of crack defects in plastic forming process. Amir[4] used the upper limit analysis method to predict the center cracking defect of a bar during extrusion in a conical mold. Fan et al[5] from Northwestern Polytechnical University simulated the composite extrusion process of rods based on the rigid plastic finite element method and predicted the internal cracking defects of the formed parts. Peng et al[6] from Shanghai Jiao Tong University simulated the bidirectional extrusion process of pure aluminum based on rigid-viscoplastic finite element method and took the stress component exceeding the uniaxial tensile strength limit of the material as the criterion of internal crack formation. Choi et al[7] used Cockcroft-Latham theory[8] as a criterion to simulate the central crack of extruded 6061 aluminum alloy. Based on the improved Rice and Tracy[9] ductile fracture criterion, Mcallen of the United Kingdom simulated the internal crack of 2011 aluminum alloy wire drawing by ABAQUS and verified it by experiments. Gui[10] from Taiyuan University of Science and Technology used the boundary element subdomain method to analyze bimetallic composite plates. The bonding strength and defects of the bonding interface in the straightening process of composite

Received date: November 10, 2022
Foundation item: Shanxi Province Patent Transformation Special Plan Project (202201006, 202202032); Shanxi Provincial Graduate Student Innovation Project (2021Y674); Taiyuan University of Science and Technology Postgraduate Joint Training Demonstration Base (JD2022002); Shanxi Province Key Research and Development Plan of Shanxi Province (202102150401002); Graduate Education Innovation Project of Taiyuan University of Science and Technology (BY2022004, SY2022007)
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plate are analyzed[11].

Lemaitre ductile fracture criterion combined with finite element simulation is a widely used method to predict the cracking of materials during plastic forming[12–14]. The Lemaitre criterion is based on the linear relationship between the damage value and the plastic strain, but the relationship between the damage value and the plastic strain of some materials is nonlinear. Wu et al[15] of Northwestern Polytechnical University modified the linear relationship between damage value and plastic strain in the original Lemaitre criterion to a nonlinear one, and obtained an improved Lemaitre criterion. Compared with the results of original Lemaitre criterion, the prediction results of the improved Lemaitre criterion are more consistent with the actual situation.

In this study, the Lemaitre criterion was improved by considering the stress triaxiality $\delta_m/\bar{\delta}$, the maximum principal stress ratio $\delta_1/\bar{\delta}$ and the influence of plastic strain on the damage. A parameter indicating the degree of cracking was proposed. The theoretical press measure was in good agreement with the simulation and experimental results. The improved criterion can effectively predict the crack generation.

1 Improved Lemaitre Criterion

In the process of sheet metal bending, the convex bending side of sheet metal is subjected to tensile stress and the concave bending side is subjected to compressive stress. According to the damage mechanics, Mises equivalent stress is used to describe the yield behavior.

Mises equivalent stress:

$$\bar{\delta} = \sqrt{\frac{(\delta_1 - \delta_2)^2 + (\delta_2 - \delta_3)^2 + (\delta_3 - \delta_1)^2}{2}} \tag{1}$$

where δ_1, δ_2 and δ_3 are principal stress.

According to the research of Yu[16], the damage variable of microholes in materials is represented by the volume fraction of holes according to the plastic potential theory of materials and the principle of constant metal volume:

$$\int_D \frac{\mathrm{d}D}{3(1-2v)(1-D)^2} = \int_{\bar{\varepsilon}} \frac{\delta_m}{\bar{\delta}} \mathrm{d}\bar{\varepsilon} \tag{2}$$

where D is the damage variable of micro holes, v is the Poisson's ratio of the material, δ_m is the Hydrostatic stress (MPa), $\bar{\varepsilon}$ is equivalent strain, $\delta_m/\bar{\delta}$ is the stress triaxiality.

According to Eq. (2), under a certain stress triaxiality, although the relationship between D and $\bar{\varepsilon}$ is nonlinear, it is not obvious and has no relation with the material itself. The study shows that when the deformation is small, D and $\bar{\varepsilon}$ are considered as linear[16]. When the deformation is large, the relationship is nonlinear. Moreover, the growth rate of voids is related to the material itself. Crack prediction is based on large deformation of the material. Therefore, it is assumed that the relationship between D and $\bar{\varepsilon}$ is power exponential and varies for different materials. So, Eq.(2) becomes:

$$\int_D \frac{\mathrm{d}D}{3(1-2v)(1-D)^2} = \int_{\bar{\varepsilon}} \frac{\delta_m}{\bar{\delta}} q\bar{\varepsilon}^p \mathrm{d}\bar{\varepsilon} \tag{3}$$

Since Poisson's ratio v and relative density of the material conform to the normal distribution relationship, when the material fails, its relative density is a fixed value and does not change with deformation. With the increase in strain, v will decrease, but the magnitude is small and negligible. So, D and v are constant. When q is shifted to the left, Eq. (3) can be expressed as:

$$\int_{\bar{\varepsilon}} \frac{\delta_m}{\bar{\delta}} \bar{\varepsilon}^p \mathrm{d}\bar{\varepsilon} = C \tag{4}$$

where C is a constant related to the generation of microholes in the large plastic deformation of plates. It reflects the size of the micropore damage variable. The physical meaning is to reflect the volume fraction of holes in the process of material deformation.

In the process of metal plastic deformation, when the plastic strain reaches a certain degree, regional damage will increase significantly, which will further affect the plastic deformation of sheet metal. Therefore, Eq.(4) is written as:

$$\int_0^{\bar{\varepsilon}_f} \frac{\delta_m}{\bar{\delta}} \bar{\varepsilon}^p \mathrm{d}\bar{\varepsilon} = C \tag{5}$$

where $\bar{\varepsilon}_f$ is the damage equivalent strain critical value of obvious cracks, $\bar{\delta}$ is the Mises equivalent stress.

According to Ref. [17], the change of the stress triaxiality $\delta_m/\bar{\delta}$ is basically consistent with the change of the maximum principal stress ratio $\delta_1/\bar{\delta}$. Changes in $\delta_1/\bar{\delta}$ are also denoted as inhibiting or accelerating the crack generation, which also affects the forming of materials. By improving Eq. (5), the ductile fracture criterion can be obtained as follows:

$$\int_0^{\bar{\varepsilon}_f} \left(\frac{\delta_m}{\bar{\delta}} + a\frac{\delta_1}{\bar{\delta}}\right) \bar{\varepsilon}^p \mathrm{d}\bar{\varepsilon} = C \tag{6}$$

where a is the influence coefficient of the maximum principal stress.

The damage model is based on damage mechanics and fracture mechanics to analyze the mechanism of crack generation from the microscopic aspect. So, the calculated value $\bar{\delta}$ is the limit value of the tensile stress in the damaged area.

2 Simulation of DEFORM-3D

In order to reflect the bending process of sheet metal, crack initiation and propagation path in the deformation process accurately and intuitively, DEFORM finite element analysis software was selected to simulate the crack generation[18].

2.1 Crack simulation of sheet metal bending forming

The three-point symmetrical bending is a large deformation process. The model and size parameters are shown in Fig. 1. Plastic body was selected for plate, imported from the material library material parameters 7075-T6. The upper die and lower die are set as rigid bodies. Define temperature, friction coefficient, upper die direction and velocity. Set board properties and unit processing methods. The number of fracture elements is set to 2, if there are more than two elements in the material whose stress reaches the critical value of fracture, these elements will be deleted and crack will occur[19].

2.2 Simulation phenomenon and result analysis

The phenomenon of simulation is shown in Fig. 2, which shows the bending force of 7075 aluminum alloy sheet with

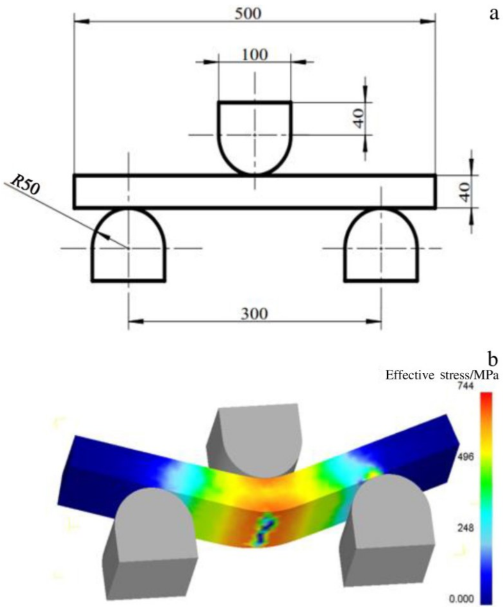


Fig.1 Three-point bending model (a) and stress cloud diagram (b)

40 mm in thickness and 300 mm in roll spacing at room temperature (20 °C). The key stress points of the plate are as follows: P_1 is the midpoint of the bottom edge, P_2 is the center point of the bottom, and P_3 is the center point of the upper surface. The position of the three points in the figure is shown in Fig.2a. According to Fig.2c–2f, the stress in the process of three-point bending forms. The first crack point is the center point of convex bending side, P_2. With the increase in the reduction amount, the crack expands to P_1, and the curves of the equivalent stress of three points under the same conditions are shown in Fig.2b.

1) In the process of bending, upper surface is compressive stress and bottom surface is tensile stress. The variation trend of the forces is roughly the same, but the value of the force is slightly different. This is due to the neutral layer offset phenomenon caused by tension-compression asymmetry[20–22]. The equivalent stress curves of P_1 and P_2 on the convex curved side coincide completely. Because of the tension on the convex curved side, the bottom surface is prone to crack defects in the deformation process.

2) With the increase in time, the equivalent stress of P_2 suddenly decreases at 28 s. No obvious crack defect appears on the surface from the stress cloud diagram of P_2 in Fig.2d. The obvious crack defects and crack propagation phenomenon is caused by the increase in the press after 28 s in Fig.2e and

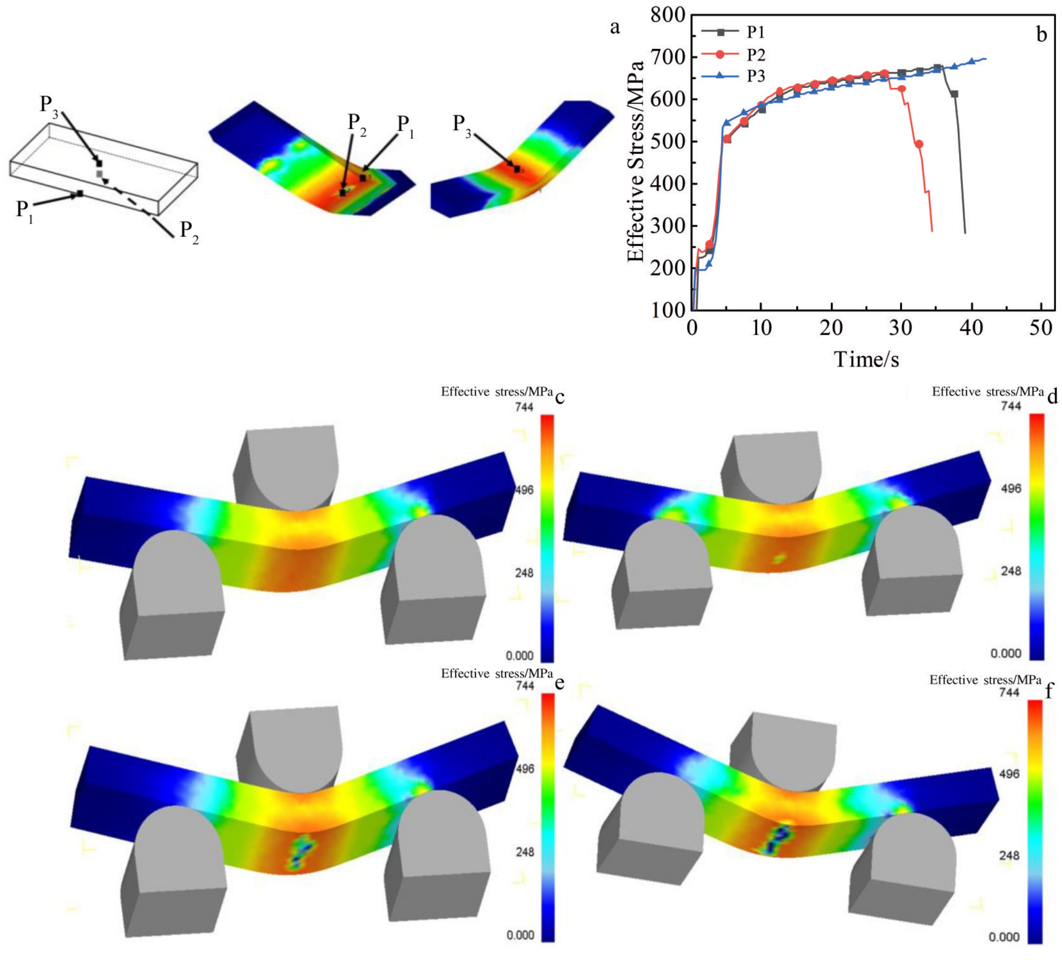


Fig.2 Position of the three points and corresponding colored stress patterns of P_1, P_2 and P_3 at initial crack generation (a); change of the stress with time at the points of P_1, P_2 and P_3 (b); change of stress in the crack extending (c–f)

2f. It is preliminarily concluded that when the force suddenly drops, the crack begins to appear. It can be used as an important reference point for crack prediction.

3) With the increase in the press measure, the equivalent stress of P_1 decreases suddenly at 36 s. This is mainly due to the crack produced at point P_2. With the application of force, the crack of P_2 expands to point P_1. The time of 36 s is also the time point when the crack of aluminum alloy plate occurs at P_1.

2.3 Determination of ductile fracture criterion parameters

The simulated data of different working conditions are shown in Table 1. $\bar{\delta}$ is mean stress, δ_m is effective stress, δ_1 is principle stress, and δ_f is equivalent strain. The values of parameters in Eq.(6) can be obtained from the data: a=2, p= –0.827, C=11.647. The fracture criterion of 7075-T6 aluminum alloy is

$$\int_0^{\bar{\varepsilon}_f}\left(\frac{\delta_m+2\delta_1}{\bar{\delta}}\right)\bar{\varepsilon}^{-0.827}\mathrm{d}\bar{\varepsilon}=11.647 \tag{7}$$

3 Experiment

The experimental material was 7075-T6 hot-rolled aluminum alloy plate with 6 mm in thickness, whose chemical composition was provided by the supplier as follows: 5.9wt% Zn, 2.7wt% Mg, 1.6wt% Cu, 0.09wt% Si, 0.28wt% Fe, 0.21wt% Cr, and the balance Al.

3.1 Test methods and data

1) Symmetrical three-point bending. The rate of upper die was 0.2 mm/min; the changes of stress-strain curves were observed during the pressing process.

2) Due to the relatively high hardness of 7 series aluminum alloy, when the first plate was bended, the roll work was not stopped in time when the crack occurred, and the sheet was broken, so the second experiment was carried out.

3) According to the experimental data of the first sheet metal, the approximate values of the force and press measure at the time of crack formation can be obtained. Combined with the numerical solution, we controlled the press measure of the second sheet metal between 8.5 and 9 mm. After the test, the sheet metal does not break, and no macroscopic cracks are produced.

4) The data of the two experiments were analyzed and processed. The variation curve of stress with displacement is shown in Fig.3.

5) The experiment is compared with the simulation results, as shown in Table 2. Metallographic experiments were carried out on the sheet metal to observe the internal structure and crack generation and different phenomena were analyzed.

Table 1 Equivalent stress and strain of crack at different roll distance *L* and plate thickness *H*

L/mm	H/mm	$\bar{\varepsilon}_f$/MPa	$\bar{\delta}$/MPa	δ_m/MPa	δ_1/MPa
250	40	0.135	663	363	763
300	30	0.157	671	361	751
300	40	0.135	663	359	765

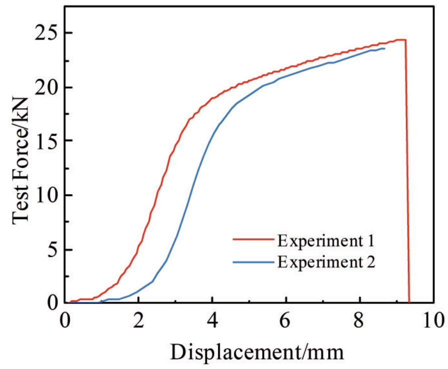
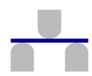
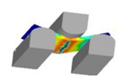
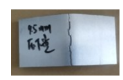
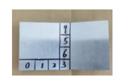


Fig.3 Experimental force-displacement curve

Table 2 Comparison between simulation and two experiments under the same working condition

Parameter	Simulation	Exp.1	Exp.2
Material code		7075-T6	
Sheet size/mm		100×50×6	
Temperature/°C		20	
Position of the upper die		Symmetric bending	
Rate of upper die/mm·min^{-1}		0.2	
Roll spacing/mm		70	
Mold drawing			
Press measure/mm	10.0	9.27	8.67
Crack	Yes	Yes	No
Consequence			

3.2 Metallographic structure observation

Metallographic structure analysis is a comprehensive analysis and determination of microstructure morphology, grain size, inclusion, defect, and composition phase, which is widely used in material science research, production inspection, failure analysis[23].

1) Sampling. In order to facilitate the observation of stress states and microstructure evolution at different positions of sheet metal during bending forming, and to make the samples representative, seven small samples were selected from the base material and numbered as 0#, 1#, 2#, 3#, 4#, 5#, 6#, as shown in Fig.4.

2) Grinding and polishing. Each sample was polished successively with metallographic sandpaper of 240#, 600#, 800#, 1000#, 1600# and 2000#.

3) Corrosion. The polished sample was corroded with Keller's reagent (2.5 mL HNO_3+1.5 mL HCL+1 mL HF+95 mL distilled water).

4) Observation and analysis. The surface of the material was observed by a metallographic microscope.

Fig. 5a shows cross section metallographic microstructure, in which the aluminum alloy substrate is a typical rolled structure, with grains elongated along the direction parallel to

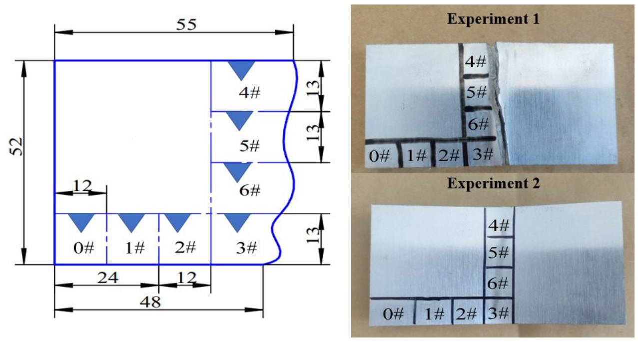


Fig.4 Schematic diagram of sampling

the surface, presenting a fibrous distribution. The fine grains of second phase and micropores are distributed inhomogeneously around the large grains. Due to the distance to the stress point, there is almost no influence of stress. The grain keeps the original rolling structure. In the process of plate bending, because there are little bending, it is mainly embodied in the tensile state (Fig. 5b and 5c), grains are elongated in the direction of the stretching, and the closer to the stress point, the slender the grain. Fig.5d shows that in the process of plate bending, convex side grain is tensile state and concave side grain is compressive state. In the stretching part, the grain is elongated in the stretching direction and the grain is relatively thin, while in the compression part, the grain is shortened along the compression direction and the grain is shorter and coarser.

Due to the distance from the stress position, there are small microholes in the plate structure, which are evenly distributed in the structure in Fig.5a–5c. The voids closer to the crack are larger and denser, the size of which is larger than that of the microholes far away from the stress position in Fig. 5d – 5g. This is due to the nucleation, growth, and polymerization process of some micropores in the sheet in plastic deformation under the action of force, which is a damage evolution process

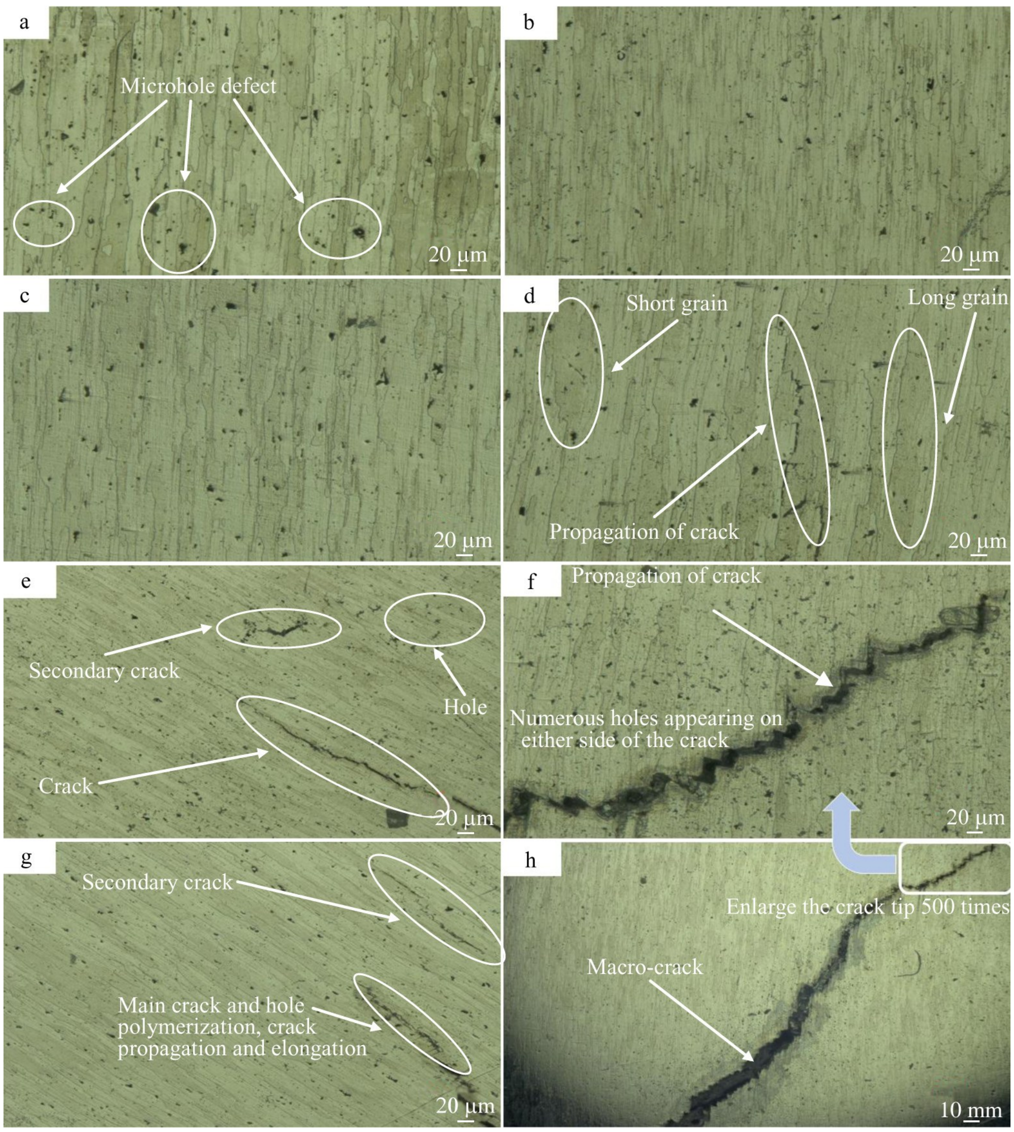


Fig.5 Metallographic microstructure of fractured plates at different stress positions in Exp.1 at room temperature: (a) 0#, (b) 1#, (c) 2#, (d) 3#, (e) 4#, (f, h) 5#, and (g) 6#

from micropores to pores and then to microcracks. Different properties will cause the disharmony of plastic deformation ability and eventually lead to fracture.

The main cracks are initiated at the root of the fracture and expand along the grain boundary in a "Z" path, and then expand perpendicular to the load direction in Fig.5d–5g. This is due to the stress concentration caused by the fracture in the bending process, and the material has a large plastic deformation, leading to crack initiation and propagation[24]. The crack mainly tends to expand along the interface between the cavity and the matrix, because the crack growth will proceed toward the weak phase with low strength and poor plasticity, so the intergranular crack is easy to form in Fig.5d and 5e. There are intergranular propagation and transgranular propagation phenomena in the "Z-shaped" propagation path of the crack in Fig.5d. Therefore, the crack propagation is the mixed mode of intergranular and transgranular propagation, and a large deflection occurs at the interface which changes the direction of propagation, rather than straight forward propagation.

Fig.5h is the macroscopic image of the crack, and crack tip enlarged by 500 times is shown in Fig. 5f. The precipitated phase at the front of the main crack is separated from the matrix, resulting in micropores. After that, the micropores grow and the main cracks expand forward and connect with each other. Some secondary cracks will occur during the primary crack expansion process in Fig. 5e and 5g. The primary crack continues to expand along the direction perpendicular to the load. The secondary crack is not connected with the primary crack, but stopped after it expands to a certain length. According to the morphology and propagation degree of cracks in Fig.5d–5g, the damage degree of the middle position is the largest in the bending process, and the damage degree on the two sides is small, which is consistent with the conclusion obtained by simulation.

As shown in Fig. 6, no crack is produced in the plate in

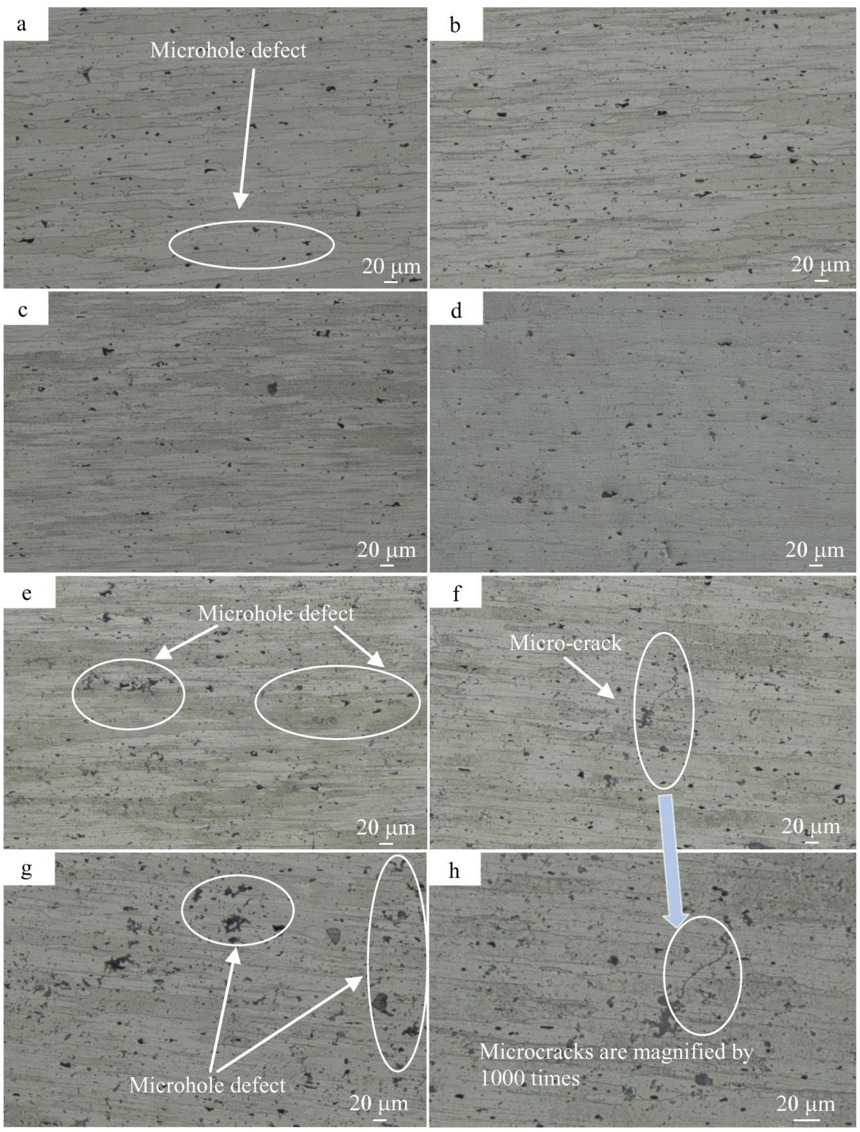


Fig.6 Metallographic microstructures of plates without obvious cracks at different stress positions in Exp.2 at room temperature: (a) 0#, (b) 1#, (c) 2#, (d) 3#, (e) 4#, (f, h) 5#, and (g) 6#

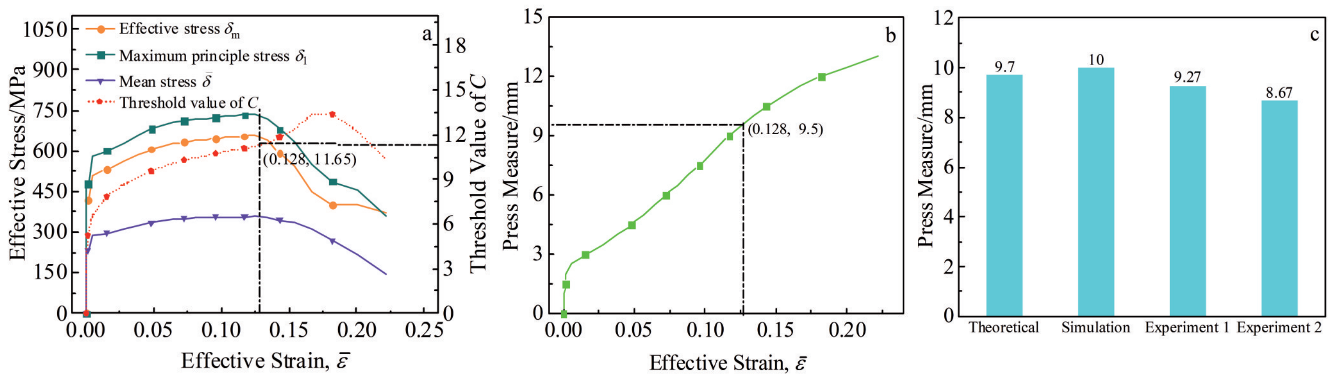


Fig.7 Curves of stress δ_m, δ_1, $\bar{\delta}$ and the threshold C as a function of $\bar{\varepsilon}$ (a); curve of press measure as a function of $\bar{\varepsilon}$ (b); comparison of press measure (c)

Exp.2. The material is rolling structure, and small micropores are distributed around the grains, as shown in Fig.6a. As the three positions in Fig. 6a–6c are far away from the load, their microstructure is less affected by plastic deformation, so the distribution of micropores is uniform. From the metallographic structure of Fig.6e–6g, there are many holes, whose size is obviously larger than that of the microholes shown in Fig.6a–6d. This is because the material has a large plastic deformation near the load, and some microholes in the plate grow up and then aggregate under the condition of plastic deformation. The microcrack is caused by the aggregation of holes from Fig.6f. In Fig.6h, the closer to the crack, the more obvious the pore polymerization. The crack initiation is transgranular, because under the action of load, the dislocation in the grain increases sharply, the roughness increases, the strength of the grain itself decreases, and the crack initiation is easy to form transgranular crack from the grain interior.

4 Verification

In order to verify the accuracy of the improved fracture criterion, the theoretical value of the fracture criterion is compared with the experimental results. The δ_m, $\delta_1$and $\bar{\delta}$ of P_2 point and the change of threshold C with $\bar{\varepsilon}$ in the bending process of plate with 6 mm in thickness are summarized in Fig.7.

In the process of force loading, when $\bar{\varepsilon}$=0.128, the threshold value of fracture criterion C=11.65, and the press measure is 9.7 mm from Fig.7a and 7b. This press measure is compared with simulation and experiment results in Fig. 7c. The theoretical value obtained by the improved fracture criterion is in good agreement with the simulation and experimental results.

5 Conclusions

1) In the bending process of the metal plate, cracks first occur at the midpoint of the convex bending side, and then expand to both sides. The damage degree at different positions in the metallological experiment verifies the conclusions obtained from the simulation.

2) In the process of plate bending, micropores are generated, and the pores polymerize to produce obvious microcracks. The cracks are initiated in the way of transcrystalline propagation, and expand in the mixed way of intercrystalline and transcrystalline propagation from the metallography experiment.

3) The improved Lemaitre fracture criterion considers the effects of stress triaxiality, maximum principal stress ratio and plastic strain on the damage. The theoretical values obtained from the prediction are in good agreement with the simulation and experiment values, suggesting that it can provide a good guiding significance for crack prediction.

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一种改进的Lemaitre断裂准则及其在弯曲成形裂纹预测中的应用

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摘　要：针对弯曲成形中的裂纹缺陷，应用Lemaitre韧性断裂准则，同时考虑应力三轴度，最大主应力比，以及塑性应变对损伤的影响，对Lemaitre准则进行改进，有效预测了弯曲成形中金属板料的成形极限。以7075-T6铝合金为研究对象，模拟得到该合金板材的裂纹产生条件，获取改进的Lemaitre准则材料参数，确定破裂阈值。对6 mm厚7075-T6铝合金板材进行三点弯曲实验，并观察其金相组织。对其产生裂纹时的压下量与断裂准则所得的理论压下量进行比较，验证了改进后断裂准则对裂纹预测的准确性。通过对比产生裂纹时的压下量，结果表明，改进后的Lemaitre断裂准则所得理论压下量为9.7 mm，与模拟和实验结果一致，证明改进后的Lemaitre准则对弯曲成形裂纹预测具有一定的准确性。

关键词：韧性断裂；Lemaitre准则；裂纹预测；7075-T6铝合金

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