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Trans. Nonferrous Met. Soc. China 21(2011) 1595−1601

Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Numerical simulation of ductile fracture behavior for aluminum alloy sheet under cyclic plastic deformation

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Received 22 June 2010; accepted 10 December 2010

Abstract: A numerical analysis of mechanical behavior of aluminum alloy sheet under cyclic plastic deformation was investigated. Forming limit at fracture was derived from Cockcroft-Latham ductile damage criterion. The strain path of bending center of incremental roller hemming could be accepted as a kind of plane strain bending deformation process. Incremental rope roller hemming could be used to alleviate ductile fracture behavior by changing the stress state of the hemming-effected area. SEM observation on the fracture surface indicates that cyclic plastic deformation affects ductile fracture mechanism.

Key words: aluminum alloy; ductile damage; incremental forming; cyclic plastic deformation

1 Introduction

Aluminum alloy, which has been used for the production of vehicle outer panels, could offer good mechanical properties depending on the chemical composition and on thermo-mechanical treatment. As a substitute of steel for light-weight design, it can make vehicles lighter, decrease fuel consumption and reduce CO_2 emissions. However, it has a weakness of low formability at room temperature, which results in the severity fracture [1−3].

Incremental sheet forming is a sheet metal forming technique where a sheet is formed by a series of small incremental deformations. The controlling program is designed according to the forming requirement of the sheet, and then a tool forms the sheet step-by-step according to a certain path by the feed system, required shape finally being satisfied. This forming process does not need dedicated forming dies [4−5]. However, incremental forming always concerns to a complex force and back forming with cyclic plastic deformation. For example, in a roller hemming process, as schematically shown in Fig. 1, a sheet is subjected to tension and subsequent compression when the roller approaches.

The limit strain before failure is called the fracture limit. Ductile damage criteria could be adopted to assess formability for aluminum alloy sheets under incremental roller hemming [6]. Some workers [7] suggest that the sheet metal the formability increases owing to the effect of strain accumulation caused by cyclic deformation. RISTINMAA [8] dealt with the ductile fracture mechanism from the view point of numerical analysis using a void unit cell model subjected to cyclic loading-unloading. GRONOSTAJSKI and MISIOLEK [9] studied the effect of strain path considering a cyclic loading on the mechanical properties and metallographic structure of copper-aluminum alloy to investigate its sheet metal formability using a cyclic torsion test. They found that the flow stress varied with cyclic torsion.

Roller hemming simulation can be applied to the process development when prototype parts are available and engineers are working on the hemming of actual panels. Simultaneous engineering in this stage can save on prototype panels, increase efficiency and productivity, and provide valuable process information.

Previous studies are mostly focused on tabletop hemming. LIVATYALI and LARRIS [10] studied the effects of flanging and hemming parameters on tabletop hemming quality through simulation and experiments.

Foundation item: Project (2010CB731703) supported by the National Basic Research Program of China; Project (0804) supported by the Shanghai Automotive Industry Corporation Foundation, China; Project (MSV-2010-03) supported by State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, China
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DOI: 10.1016/S1003-6326(11)60902-3

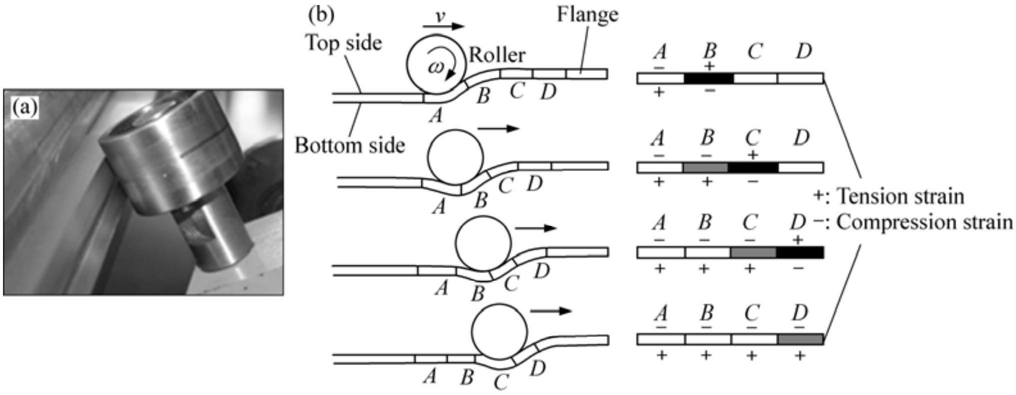

Fig. 1 Cyclic plastic deformation for incremental forming: (a) Roller hemming process; (b) Strain state during roller hemming process

ZHANG et al [11] investigated the mechanism of tabletop hemming warp and recoil. MUDERRISOGLU et al [12] analyzed the influences of flanging parameters on roll-in/out of 1050 aluminum alloy tabletop hemming. LIN et al [13] presented the maximum surface strain as a hemming fracture criterion. For roller hemming process, THUILLIER et al [14] focused on the finite element simulation of roller hemming process of an Al-Mg alloy on roll-in/out. However, the fracture behavior of the aluminum alloy was not studied yet.

This paper presents a study on the mechanical behavior of aluminum alloy sheets during cyclic plastic deformation. The adoption of forming limit based on ductile criterion is illustrated to predict fracture for aluminum alloy under cyclic plastic deformation. Finally, the cyclic hardening behaviors of materials, the alleviation of fracture for incremental roller hemming and fractograph observations for the ductile fracture are investigated.

2 Constitutive model and parameter identification

The aluminum alloy sheet 6061-T6 is considered in the present investigation and its chemical composition is listed in Table 1.

Table 1 Chemical composition of aluminum alloy 6061-T6 (mass fraction, %)

Mg	Si	Cu	Cr
0.8−1.2	0.4−0.8	0.15−0.40	0.04−0.35
Fe	Mn	Zn	Ti
≤0.7	≤0.15	≤0.25	≤0.15

A phenomenological constitutive model with an isotropic yield criterion, a non-linear kinematic hardening rule and an associated flow rule for 6061-T6 roller hemming is presented in this section.

The yield criterion which defines the elastic domain is written in the form:

$$f(\sigma_{ij}) = \sigma_{\mathrm{eq}} - \sigma_{\mathrm{y}}(\bar{\varepsilon}_{\mathrm{p}}) \le 0 \quad (1)$$

where $\sigma_{\mathrm{y}}(\bar{\varepsilon}_{\mathrm{p}})$ defines the yield stress in the form:

$$\sigma_{\mathrm{y}}(\bar{\varepsilon}_{\mathrm{p}}) = \sigma_{\mathrm{y0}} + R(\bar{\varepsilon}_{\mathrm{p}}) \quad (2)$$

where σ_{y0} is the initial yield stress; $\bar{\varepsilon}_{\mathrm{p}}$ is the accumulated effective plastic strain with the definition:

$$\bar{\varepsilon}_p = \sqrt{\frac{2}{3}\varepsilon_{ij}^{\mathrm{p}}\varepsilon_{ij}^{\mathrm{p}}} \quad (3)$$

where $\varepsilon_{ij}^{\mathrm{p}}$ is the plastic strain; σ_{eq} is the effective stress which is defined by Mises yielding

$$\sigma_{\mathrm{eq}} = \sqrt{\frac{3}{2}(\sigma_{ij} - \alpha_{ij})^2} \quad (4)$$

where σ_{ij} and α_{ij} are the flow stresses and back stresses, respectively.

A combined isotropic and nonlinear Lemaitre and Chaboche kinematic hardening model [15] is introduced to roller hemming taking into consideration of reverse loading.

The evolution equation for R is the isotropic hardening rule with saturation as

$$\mathrm{d}R = b(Q - R)\mathrm{d}\bar{\varepsilon}_{\mathrm{p}}, \ R=0 \ \text{when} \ \bar{\varepsilon}_{\mathrm{p}}=0 \quad (5)$$

where Q and b are material parameters.

The associated flow rule is used in the form:

$$\mathrm{d}\varepsilon_{ij}^{\mathrm{p}} = \frac{\partial f(\sigma_{ij})}{\partial \sigma_{ij}}\mathrm{d}\bar{\varepsilon}_{\mathrm{p}} \quad (6)$$

The nonlinear Lemaitre and Chaboche kinematic hardening model has two parameters to describe kinematic hardening component, which is defined to be an additive combination of a purely kinematic term and a relaxation term, which introduces the nonlinearity. The evolution law is

$$\mathrm{d}\alpha_{ij} = C\frac{1}{\sigma_{\mathrm{y}}(\bar{\varepsilon}_{\mathrm{p}})}(\sigma_{ij} - \alpha_{ij})\mathrm{d}\bar{\varepsilon}_{\mathrm{p}} - \gamma\alpha_{ij}\mathrm{d}\bar{\varepsilon}_{\mathrm{p}} \tag{7}$$

where C and γ are material parameters.

The material constitutive model already integrated in ABAQUS/EXPLICIT is used in this project with defining the isotropic hardening part and kinematic hardening part accordingly.

6061-T6 is an aluminum alloy with elastic modulus of 66.6 GPa and Poison's ratio of 0.33. Other material parameters (σ_{y0}, Q, b, C, γ) must be identified from uniaxial tension and compression tests. In order to prevent buckling during compression, four pieces of the sheets were adhesively bonded together before testing with a special specimen holder which is shown in Fig. 2.

The following two cases in Fig. 3 were conducted to determine the accurate material parameters for the combined hardening of 6061-T6 aluminum alloy.

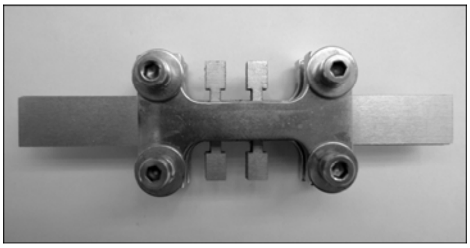

Fig. 2 Specimens holder

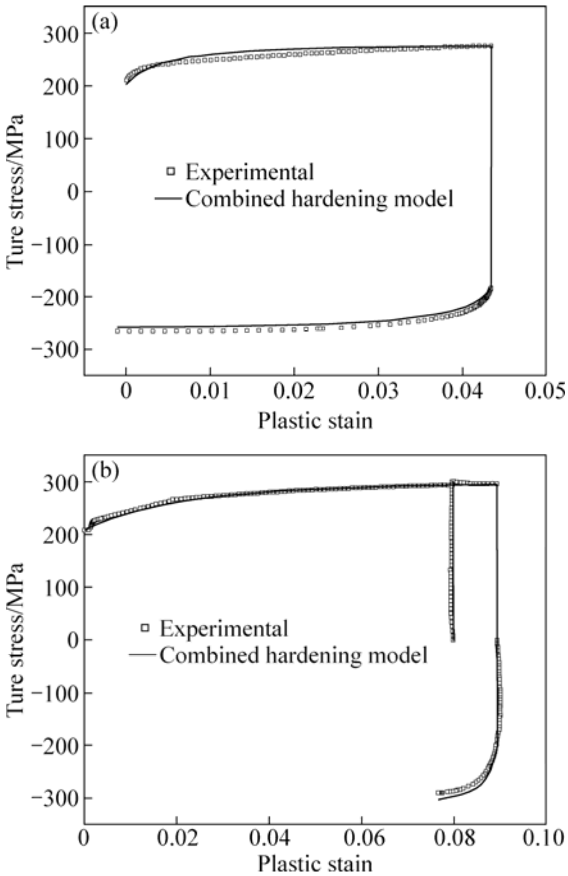

Fig. 3 Typical uniaxial tension and compression test studies: (a) Uniaxial tensile test until failure; (b) Full cycle of tension and compression

The parameters determined from these two cases are listed in Table 2.

Table 2 Combined hardening parameters

σ_{y0}/MPa	Q/MPa	b	C/MPa	γ
209.2	38.9	21.1	3529.3	65.16

3 Ductile fracture

3.1 Fracture limit

Forming limit strain curve is always associated with linear strain paths. Forming limit stress curve which is previously thought to have no connection with strain path complexity could be proposed as a criterion to determine fracture limit.

The ductile fracture criterion proposed by COCKCROFT and LATHAM [16] is considered, which assumes fracture happens when $W = \int_0^{\bar{\varepsilon}} \max(\sigma_1, 0)\mathrm{d}\bar{\varepsilon} \geq W_{\mathrm{C}}$, where σ_1 is the maximum principal stress and W_{C} is the critical value of the integral W. W_{C} could be determined from uniaxial tensile experiment [17].

Effective strain is generally considered a function of stress triaxiality. This dependency is always referred to be fracture locus in ductile fracture criteria [18]. The hydrostatic stress σ_{h} and $\bar{\sigma}$ are both the function of the linear strain ratio and the major stress. Then the stress triaxiality $\sigma_{\mathrm{h}}/\bar{\sigma}$ is the function of α by eliminating the common major stress. Finally, the stress triaxiality $\sigma_{\mathrm{h}}/\bar{\sigma}$ and fracture strain $\bar{\varepsilon}$ could be obtained based on any given strain ratio α which could be found in Fig. 4.

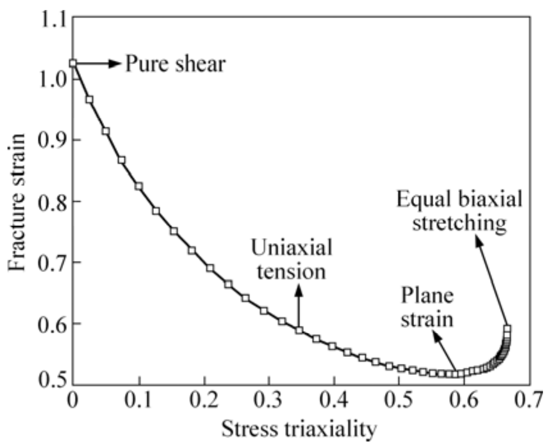

Fig. 4 Fracture limit based on ductile damage criterion

3.2 Experimental verification

Incremental roller hemming experiments and simulations were conducted to verify the feasibility of constitutive model and ductile fracture of aluminum alloy sheet.

Experiments were taken out based on the tools setup described in Fig. 5. The inner blank and outer blank were clamped by the flat binder through force applied by the fixture which was mounted on the working table. The roller was the tool which was progressively bending the outer flanging.

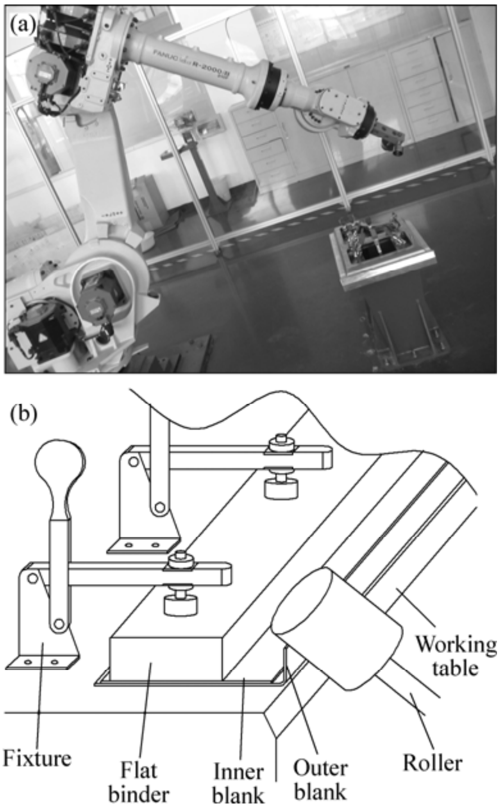

Fig. 5 Experimental tools: (a) Experimental tool establishment; (b) Description of related tools

Simulation was conducted through the ABAQUS/ EXPLICIT for incremental roller hemming. A flat panel with straight edge was used in this simulation. The flat surface-straight edge sample has a length of 200 mm and width of 60 mm. The inner blank has 200 mm in length and 42 mm in width.

The results illustrated that fracture happened at the bending center near the free edge, which is in accordance with the experimental result very well shown in Fig. 6.

Hence, ductile damage criteria could be used to predict fracture behavior of aluminum alloy sheet under cyclic plastic deformation.

4 Results and discussion

4.1 Cyclic plastic deformation

Figure 7 shows the strain path of the bending center (the featuring point in Fig. 6) over the whole incremental roller hemming process. Strain path seems to have unobvious serrations. This phenomenon could be induced by the cyclic hardening behavior of incremental roller hemming. However, the path still oscillates around the plane strain deformation line. Hence, the strain path of bending center of incremental roller hemming could be accepted as a kind of plane strain bending deformation process.

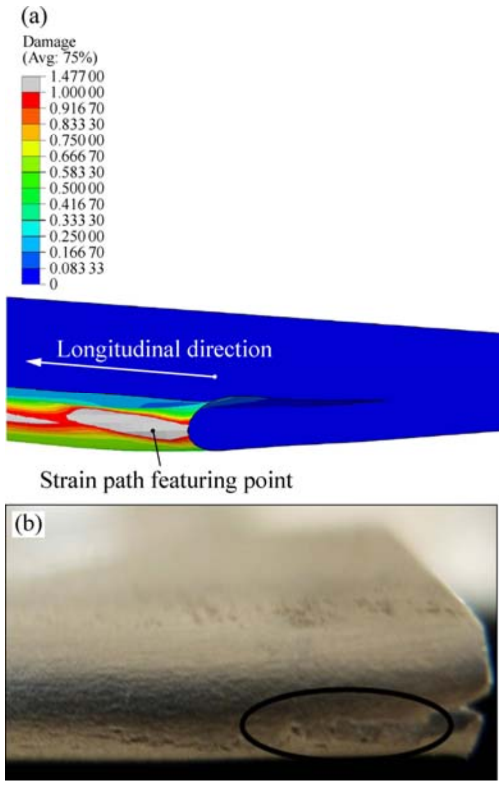

Fig. 6 Damage locations: (a) Simulation; (b) Experiment

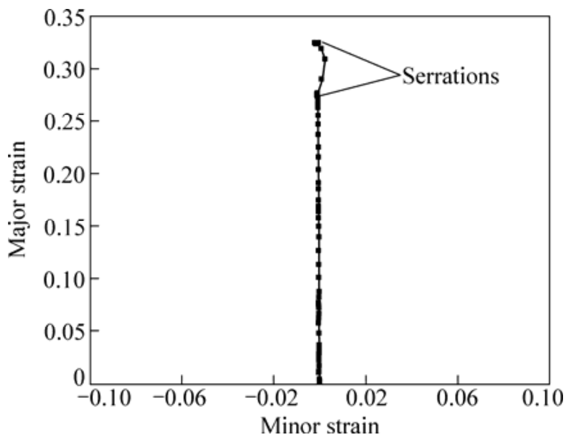

Fig. 7 Strain path of bending center

Figure 8 shows the longitudinal stress state of the bending center during the incremental hemming process where hemming time scale means the simulation time. The stress state diagram has two fluctuations, which is in accordance with the cyclic hardening phenomenon described in Fig. 7. Both of the figures hold onto the idea that roller hemming concerns to a kind of cyclic hardening behavior.

4.2 Alleviation of fracture

The decreasing of bendability in aluminum alloy often requires the use of rope roller hemming (versus flat roller hemming for steel), which could be described in Fig. 9. Flat hemming (Fig. 9(a)) always refers to a kind of 3 times of thickness hemming (*t*), while rope hemming (Fig. 9(b)) means a more than 3 times of thickness hemming characterized by a rope producing during final hemming process.

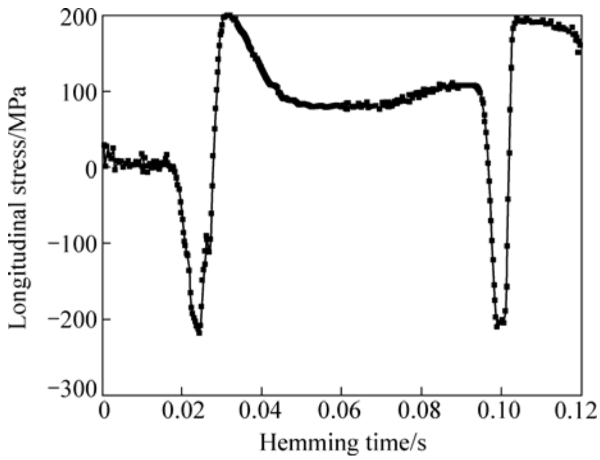

Fig. 8 Longitudinal stress state of bending center

Fig. 9 Different incremental roller hemming types: (a) Flat hemming; (b) Rope hemming

The stress magnitude over the hemming-affected area is much higher than that over the little plastic deformation area (Fig. 10). For flat roller hemming, the maximum stress of the hemming-affected area is as high as 254.5 MPa at the bending center at hemline, while the minimum stress is 25.7 MPa. The difference of Mises stress over the hemming-affected area of flat roller hemming comes to as high as 228.8 MPa. Then for rope roller hemming, the maximum stress tends to be 212.6 MPa at conjunction of rope and flat hemmed edge, while the minimum stress is just 43.2 MPa. The difference between the maximum and minimum Mise stress is 169.4 MPa.

Hence, flat roller hemming concerns to a greater stress difference over the hemming-affected area compared with rope roller hemming, which brings out the severity of fracture behavior during flat roller hemming.

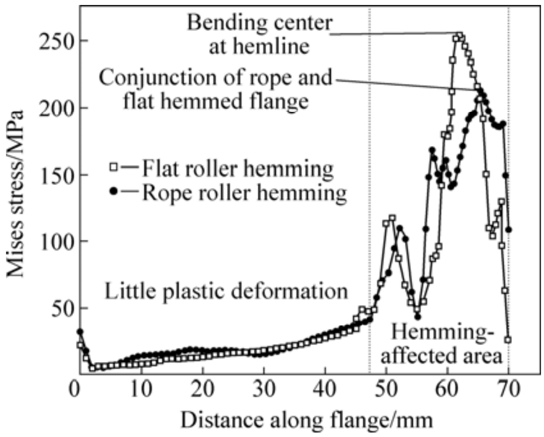

Fig. 10 Stress distribution along flange direction

4.3 Fractograph observation

Figure 11 shows the fractograph obtained by scanning electron microscopy (SEM) in both the uniaxial tensile and incremental roller hemming cases with the same original thickness of 1 mm. It could be spotted that necking is the failure limit for tensile test with an obvious thinning in the fracture surface, while fracture is the forming limit for incremental forming without any sign of visible thinning.

Figure 12 shows the fractograph obtained by SEM in tensile test. A typical fracture surface is observed both

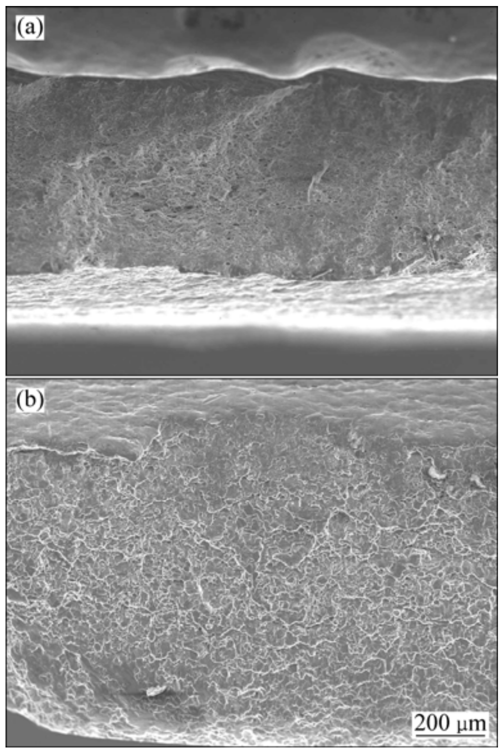

Fig. 11 SEM images of fracture surface: (a) Tensile test; (b) Incremental roller hemming test

for the top and bottom sides. Voids are observed visibly, while the dimples are spherical.

Figure 13 shows the fractograph obtained by SEM in incremental roller hemming test. The appearance of dimples is different for that in the uniaxial tensile test. The dimples are parabolic-shaped. Fewer and smaller voids are observed particularly on the bottom inner side than on the top outer side, while a typical fracture surface is observed in the fractograph of the tensile test specimen. It can be inferred that both void nucleation and growth processes are suppressed by the cyclic strain effect.

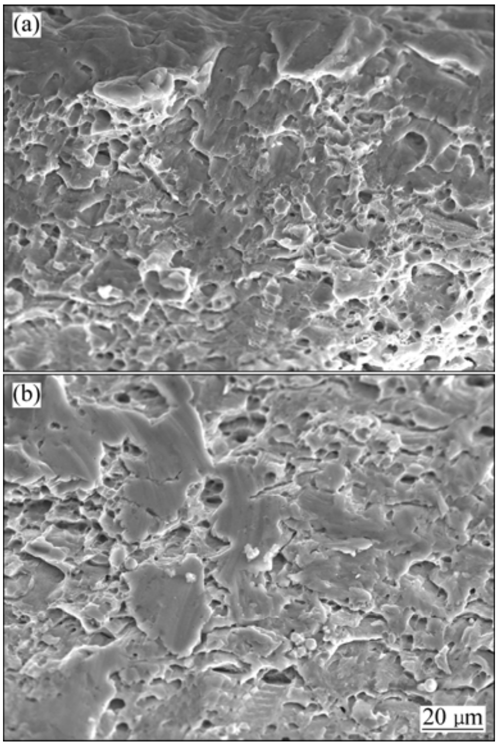

Fig. 12 SEM images in tensile test: (a) Top side; (b) Bottom side

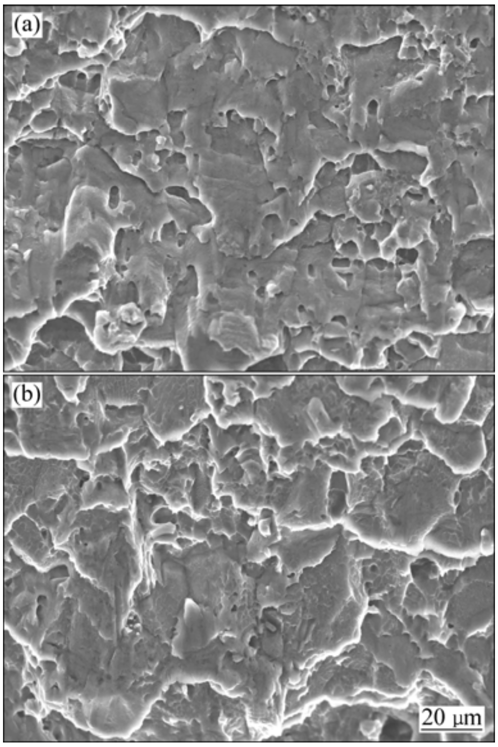

Fig. 13 SEM images in incremental roller hemming test: (a) Top side; (b) Bottom side

5 Conclusions

1) A combined isotropic and kinematic hardening rule was used. And the parameters of the combined hardening model were identified through uniaxial tension and compression tests.

2) Cockcroft-Latham ductile fracture criterion was taken to predict fracture limit for aluminum alloys under cyclic plastic deformation. The simulation and experimental results demonstrated that Cockcroft-Latham ductile fracture criterion was helpful to evaluate formability for aluminum alloy sheet under cyclic plastic deformation.

3) Incremental rope roller hemming could be used to alleviate ductile fracture behavior by changing the stress state of the hemming-affected area. SEM observation on the fracture surface indicated that cyclic plastic deformation affects ductile fracture mechanism.

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铝合金板在循环塑性变形下的韧性断裂行为模拟

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摘 要：基于数值模拟的方法研究在循环塑性变形下铝合金板的力学行为。首先，通过 Cockcroft-Latham 韧性断裂准则得到材料的断裂极限应力图，并通过实验对成形极限应力图进行验证。数值模拟结果表明：滚边时弯曲中心的应变路径可以认为是平面应变状态；采用绳式滚边方法可以改善在弯曲中心线上的应力集中现象。从滚边断口的扫描电镜照片可以发现，循环塑性变形对铝合金板的韧性断裂行为有影响。

关键词：铝合金；韧性断裂；增量成形；循环塑性变形

(Edited by YANG Hua)