Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 1602-1606

Prediction of Fracture of Aluminium Alloy with Surface Flaw in Upsetting

Misao ITOH [1] and Ai SASAKI [2]

[1] Kisarazu National College of Technology ,2-11-1Kiyomidai-higashi Kisarazu, Chiba, JAPAN

[2] Yamaha Fine Technologies Co. Ltd., 283 Aoya-Cho, Minami-Ku Hamamatsu, Shizuoka, JAPAN

The upsetting of a less ductile aluminium alloy A6061-T6 is conducted to investigate the effect of initial surface flaw on fracture. A prediction of surface cracking by means of three fracture criteria is attempted. For the specimen with longitudinal flaw, upsetting limit decreases with flaw depth more than 0.05mm, and crack initiates at flaw root. For the specimen with circumferential flaw, upsetting limit is independent of flaw length, and crack initiate at specimen surface. From these results, longitudinal flaw leads to earlier surface cracking, while circumferential flaw does not affect surface cracking. Oyane's criterion, which is based on void growth and under triaxial stress state, can well predict the surface cracking by using the stress and strain at flaw root calculated by FEM. A new parameter, based on an accumulation of maximum shearing stress on the flaw surface along the deformation path, is proposed. The experimental data about the orientation of crack are in good agreement with the predictions by the parameter proposed.

Keywords: *ductile fracture, upsetting, surface flaw, prediction of fracture, crack mode.*

1. Introduction

The demand for lightweight and high-performance vehicles has been increased in recent years. Therefore, there has been a dramatic and steady growth of aluminium alloys for automotive applications. Different aluminium alloys are specified or developed for different automotive parts according to specific performance requirements for strength, hardness, formability, crash-worthiness, corrosion resistance, fatigue resistance, weldability, etc.

Most of parts, which are demanded for complex shape and strength, may be formed by plastic deformation processing, such as cold-forging, from simple rods or sheets. It is considered possible that the surface flaw on the raw materials is caused by improper forming condition such as wear of the tool or friction. High strength material is sensitive to surface flaw, generating during being formed into simple shapes such as rods and sheets. Therefore, it is necessary to investigate the influence of the surface flaw in the cold-forging on fracture quantitatively.

Cracking in materials designated for forging operations generally occurs by ductile fracture mechanisms. The ductile fracture limits in metals is influenced by surface flaw occurred during extrusion and rolling. The limit of the forming process is governed by a complicated interplay of such factors as material structure (the nature of the second phase particles, inclusion, etc.), temperature, rate of deformation, tool and workpiece geometry and the friction at the interface of the workpiece.

Cold upsetting of a circular cylinder is often used to evaluate the cold forgeability[1]. This simple laboratory test (usually performed quasi-statically) is obviously not representative of many industrial forging operations. However open die forging and heading can be regarded as upsetting operations and the laboratory test does permit a comparison to be made between different materials in an upsetting process.

In this study, upsetting of a less ductile aluminium alloy A6061-T6 is performed to investigate the effect of initial flaw on fracture. A prediction of surface cracking by means of three fracture criteria is attempted. A parameter for prediction of orientation of crack is proposed.

2. Experimental Procedure and Method of Analysis

2.1 Material and Specimen Geometry

The material used in the experiment is a less ductile aluminium alloy A6061-T6. Test specimen for upsetting is a circular cylinder which has the diameter of D_0=12mm, height of H_0=26.4mm. The specimens are a normal cylinder without surface flaw and a cylinder with a flaw on the surface as shown in Fig.1.

Gauge marks are stamped by the micro-vickers hardness tester on each test piece at its mid-height to calculate a strain path. The CCD camera is used for the detection of a crack originated on the surface and for capture of the image of gauge marks during the upsetting test.

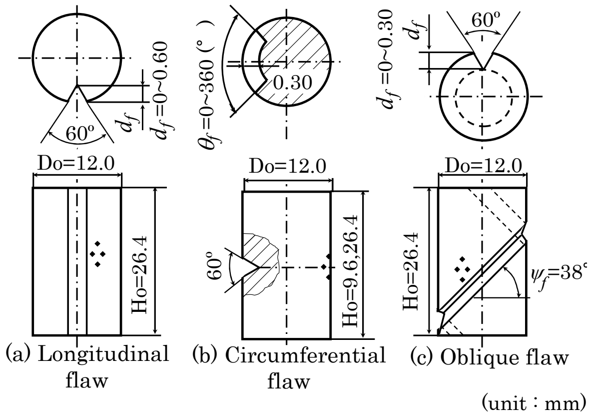

Fig. 1 Specimen geometry and flaw direction

2.2 Method of Analysis

The hoop, ε_θ and axial, ε_z , strains are determined from the measurement of variation of displacement between surface gauge marks. From measured strain on the specimen surface, the stresses are determined by using the Levy-Mises' stress-strain increment relation on the assumption of isotropy.

The finite element code ANSYS ver.11.0 is employed in the present work to estimate stress and strain path on the surface of specimen and compared with the above simple plasitic theory. The analitical FE model and mesh are shown in Fig.2. In the present analysis, the frction coeffcient between specimen and tool interface is decied by adjusting good agreement of the specimen shape during deformation between FEM and experiment.

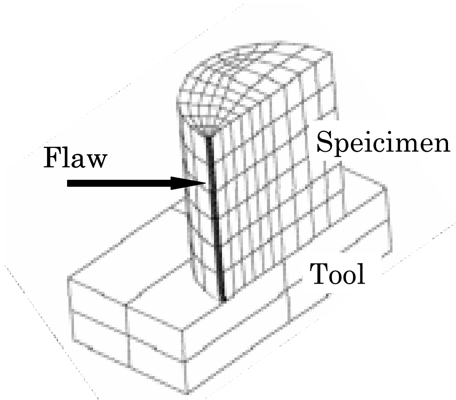

Fig. 2 Analitical model and FE mesh

2.3 Fracture Criteria

To predict the surface cracking, we must have the fracture criterion. It has been known that the initiation of surface or internal cracking in metals strongly depends on the stress and strain histories, and many ductile fracture criteria have been proposed in taking account of the histories. In this paper, three fracture criteria : McClintock's, Cockcroft & Latham's and Oyane's are used and checked which of them is the most suitable for the prediction of upsetting limits.

McClintock [2] proposed a fracture criterion based on the concept of void growth

$$\phi_m = \int_0^{\varepsilon_f} \left[\frac{\sqrt{3}}{2(1-n)} \sinh \left\{ \frac{\sqrt{3}(1-n)}{2} \frac{\sigma_1 + \sigma_3}{\sigma_{eq}} + \frac{3}{4} \frac{\sigma_1 - \sigma_3}{\sigma_{eq}} \right\} \right] d\dot{\varepsilon}_{eq} \qquad (1)$$

where σ_1 and σ_3 denote the maximum and minimum transverse stresses, n is the work hardening exponent and ε_f is the representative fracture strain. Equation (1) means that the fracture occurs when the void grows to a critical size of ϕ_{mc}.

Cockcroft and Latham [3] assumed that the fracture is controlled by the maximum stress $\sigma_{\max}$ and proposed the following criterion.

$$\phi_c = \int_0^{\varepsilon_f} \sigma_{\max} d\varepsilon_{eq} . \tag{2}$$

Oyane [4] considered a void growth model and postulated that

$$\phi_o = \int_0^{\varepsilon_f} \left[C_1 + \frac{1}{C_2} \frac{\sigma_m}{\sigma_{eq}} \right] d\varepsilon_{eq} . \tag{3}$$

where σ_m is the hydrostatic stress and C_1 and C_2 are material constants determined by the experiments. This criterion tells us that the fracture is controlled by triaxiality of stress ,σ_m / σ_{eq}.

The above three criteria have a integral form , where fracture occurs when the damage parameters of ϕ_m ,ϕ_c and ϕ_o reach some particular critical values of ϕ_{mc} ,ϕ_{cc} and ϕ_{oc}. To calculate the development of the damage parameters in the above mentioned fracture criteria, some stress quantity over a strain path of a workpiece must be known.

3. Results and Discussion

3.1 Experimental Results

Figure3 shows the variation in the upsetting limit $\phi_f = (H_0 - H_f)/H_0 \times 100$ % with flaw angle ψ_f. For the specimen with a circumferential flaw the upsetting limit ϕ_f is 73%, while for the specimen with a longitudinal flaw the value decreases to 58%. The upsetting limit of the specimen without a flaw was the same as that of the specimen with a circumferential flaw. Thus, the upsetting limit of the specimen with a circumferential flaw is not affected by the existence of a flaw because the flaw closes during deformation. On the other hand, that with a longitudinal flaw is lower because the cracking occurs at the flaw root.

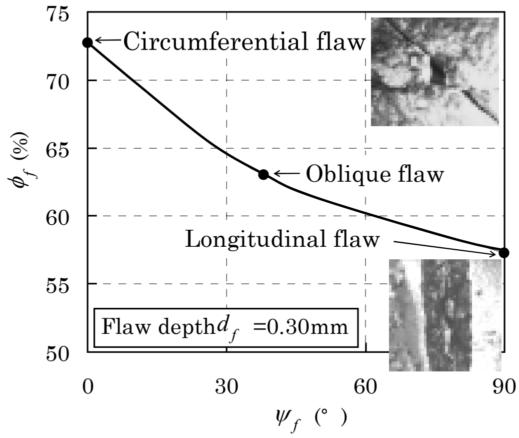

Fig. 3 Variation in upsetting limit ϕ_f with flaw angle ψ_f

Figure4 shows the variation in the upsetting limit ϕ_f with the flaw depth d_f. For both a oblique and a longitudinal flaw, the upsetting limits decrease rapidly from a certain flaw depth which is 0.20mm or 0.05mm respectively. The place of cracking is at the flaw root for the longitudinal flaw and that is not at flaw root for the oblique flaw. From above results, it is considered that for the fracture, a critical flaw depth exists.

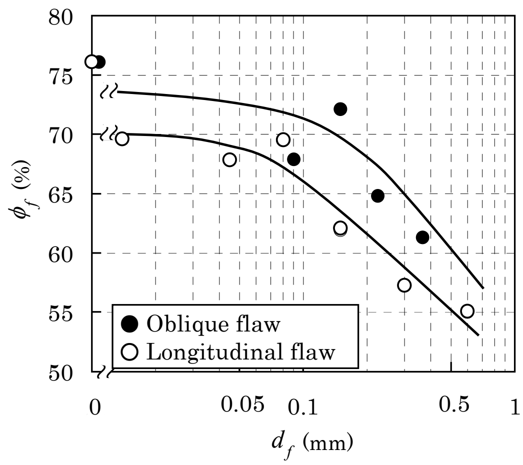

Fig. 4 Variation in upsetting limit ϕ_f with flaw depth d_f

3.2 Prediction of Upsetting Limits

The predicted results for the surface cracking by means of above mentioned three the fracture criteria , i.e., McClintock's , Cockcroft & Latham's and Oyane's, are compared with the corresponding experimental results. All these criteria describe the effect of flaw on the upsetting limits qualitatively. Especially Oyane's criterion can well predict the upsetting limit, therefore, this article describes the results predicted by Oyane's criterion. In Oyane's criterion , the fracture occurs when the integral of ϕ_o over the strain path reaches $1.0 (= \phi_{oc})$.

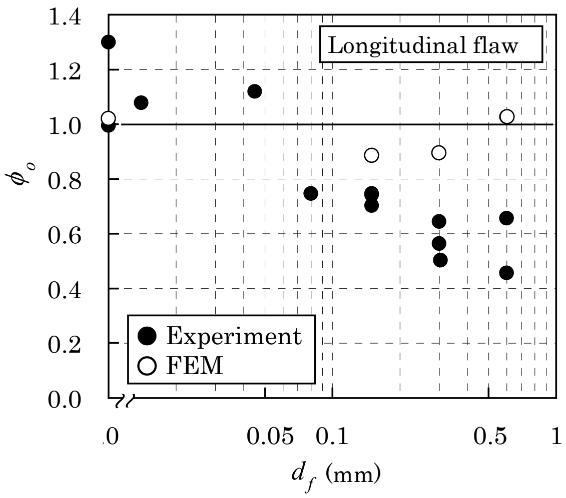

Figure5 shows the variation in the damage parameter ϕ_o with the flaw depth d_f . The prediction of the upsetting limit by the use of stress and strain calculated from the measurement of displacement between gauge marks(●) is difficult, because ϕ_o is not constant, i.e., ϕ_o decreases with the flaw depth d_f . But the prediction of the upsetting limit by the use of the stress and strain at the flaw root calculated by FEM(○) is possible, i.e., ϕ_o is almost a constant value of 1.0.

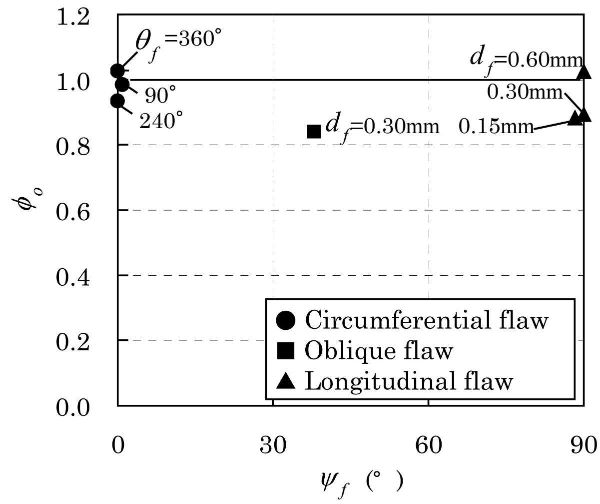

Fig. 6 Variation in damage parameter ϕ

Figure6 shows the variation in the damage parameter ϕ_o calculated by FEM with flaw angle ψ_f . The damage parameters ϕ_o calculated for various flaw geometries are almost on the line of $\phi_o = 1.0$ and ϕ_o is independent of both flaw depth d_f and flaw angle θ_f . From the above results, it is considered that the prediction of cracking of workpiece in cold forging operation is possible, if Oyane's criterion and FEM are used for the prediction.

3.3 Prediction of Orientation of Cracking

The orientation of cracking was found to coincide with the direction of maximum shear by Kudo and Aoi. This idea has been widely supported by many experimental results, however, the idea was not taken into consideration of the strain path up to the cracking.

The authors propose a new parameter Φ which is taking account of the strain path and has the following integral form,

$$\Phi = \int_0^{\gamma_{1f}} \tau_1 \, d\gamma_1 - \int_0^{\gamma_{3f}} \tau_3 \, d\gamma_3 \tag{4}$$

where τ_1 and γ_1 are the maximum shear stress and strain in the case of occurrence of the oblique crack, τ_3 and γ_3 are the maximum shear stress and strain in the case of occurrence of the longitudinal crack.

Figure7 shows the variation in proposed parameter Φ with the aspect ratio of specimen Ho/D. Experimental data approximately lie on the one linear line. The orientation of cracking can be decided by the value of Φ, namely the oblique crack occurs when the value of Φ is greater than 150MPa, while the longitudinal crack occurs when that is less than 150MPa.

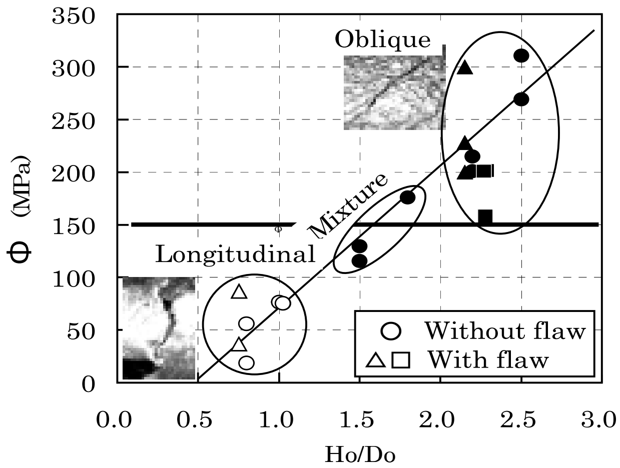

Fig. 7 Variation in Φ with aspect ratio Ho/D

4. Conclusions

Cold upsetting of a less ductile aluminium alloy A6061-T6 using circular cylinder with a surface flaw are conducted to evaluate the effect of surface flaw on ductile fracture. A prediction of surface cracking by means of three fracture criteria is attempted. A parameter for the prediction of orientation of crack is proposed. The results obtained are summarized as follows:

(1) For the specimen with longitudinal flaw, the upsetting limit decreases with the flaw depth more than 0.05mm, and the crack initiates at flaw root. For the specimen with a circumferential flaw, upsetting limit is independent of the flaw length, and the crack initiates at specimen surface. From these results, the longitudinal flaw leads earlier surface cracking, while the circumferential flaw does not affect the surface cracking.

(2) Oyane's criterion, which is based on void growth and under triaxial stress state, can well predict the surface cracking by using the stress and strain at flaw root calculated by FEM.

(3) The experimental data for the orientation of crack are in good agreement with the predictions by the parameter proposed.

Acknowledgement

The authors would like to thank Mr. M. Yamamori, Mr. A. Fujii and K.Saitoh of Chiba University for their contributions to this work.

References

[1] H. Kudo and K.Aoi: J. Japan Soc. Tech. Plasticity. 8(1967)17-27.
[2] F. A. McClintock: Trans. ASME, J. Appl. Mech. 35(1968) 363-371.
[3] M. G.Cockcroft and D.J. Latham : J. Inst. Metals. 96(1968)33-39.
[4] M.Oyane: Bull. JSME.l(1972)1507-1513.