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〈논 문〉

Ductile Fracture in the Central Region of Circular Plate in Rotary Forging

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Abstract

The present investigation is concerned with the application of theory on fracture to the prediction of workability of materials in rotary forging, with special reference to center crack. The validity of the theory on ductile fracture was examined by the experimental data. Then the workability of materials in rotary forging was determined.

Key Words: Metal Forming Process, Ductile Fracture, Rotary Forging Process, Upsetting, Central Crack

1. Introduction

An accurate determination of the effects of various parameters on metal flow and fracture is a prime requirement for proper design and control of any metalworking process. Without the knowledge of the influence of such variables as friction conditions, materials properties, and process geometry on the process mechanics, it would not be possible to control the change of the metallurgical structure of the deforming material, or to predict and prevent the occurrence of defects. By combining the detailed information on mechanics and the ductile fracture criterion, workability of materials in metalworking processes can be predicted predicted.

The new ductile fracture criterion proposed in the previous paper[1] was developed from the theory of fracture toghness under different mean stress from tensile test. The elongation at fracture decreases linearly with increases of depressive mean stress and the decreasing gradient is determined by the line from yield point to ultimate tensile point in the uniaxial tensile test.

The present investigation has as its object the provision of experimental data for the validity of the proposed new ductile fracture criterion. The validity of the proposed new ductile fracture criterion was examined by the experimental data which are given from upsetting experiments in the rotary forging.

2. Proposed New Ductile Fracture Criterion

Ref. 2 shows about the fracture toughness under different mean stress from tensile test that if plastic deformation occurs under different mean stress from tensile test, the elongation, the surface energy per unit area and the fracture toughness are changed because the atomic bonding force decreases or increases with mean stress.

Because the mean stress in uniaxial tensile test is on third of the axial stress, variation of mean stress is equivalent to three times effect in uniaxial stress.

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The elongation change caused by mean stress variation is $(-\Delta\sigma_m/\tan\theta)$ in Fig. 1.

The changed surface energy per unit area is as follows

$$\gamma_p=\gamma_s\frac{\left\{\left(\frac{\Delta l}{l_o}\right)_f-\frac{\Delta\sigma_m}{\tan\theta}\right\}}{(\sigma_u-\Delta\sigma_m)/E} \tag{1}$$

where γ_p is total surface energy per unit area, γ_s is brittle elastic surface energy per unit area, $\Delta\sigma_m$ is mean stress variation (i.e. $(\sigma_1+\sigma_2+\sigma_3)/3$), E is Young's modulus of elasticity and σ_u is the ultimate tensile strength.

The proposed new ductile fracture criterion then is as above[1]

$$\left(\frac{\Delta l}{l_o}\right)_{fat\Delta\sigma_m}=\left(\frac{\Delta l}{l_o}\right)_f+\left(\frac{-1}{\tan\theta}\right)\Delta\sigma_m \tag{2}$$

where $(\Delta l/l_o)_{fat\Delta\sigma_m}$ is fracture elongation of material at any state of stress, $(\Delta l/l_o)_f$ is fracture elongation obtained from tensile test.

The new criterion means that the material endures elastic and plastic deformation to the time when the mean stress reaches to the maximum sustainable equicohesive bonding stess. As the temperature rises the thermal vibration energy makes the equicohesive stress decrease. And also at a cretain temperature and stress state the cohesive force decreases as the time elapses. If the variation of mean stress at a point in the material under the hydrostatic state is $\Delta\sigma_{m1}$, see Fig. 1, the fracture elongation of the material is changed from $(\Delta l/\Delta l_o)_f$ to $(\Delta l/l_o)_{fat\Delta\sigma m1}$. The fracture elongation of the material is increased. On the contary, if the material is in the tensile stress state and the variation of mean stress is $\Delta\sigma_{m2}$, the fracture elongation of the material is changed from $(\Delta l/l_o)_f$ to $(\Delta l/l_o)_{fat\Delta m2}$. The fracture elongation of the material is decreaed.

Therefore temperature rise, time elapse and depressive mean stress's increase reduce the equicohesive bonding stress in the material. The material fractures at the time when the equicohesive bonding stress can not sustain external mean stress. The palstic deformation also reduces the equicohesive bonding stress by damaging its microstucture.

3. Ductile Fracture in the Central Region of Billet in Rotary Forging

The mechanics and mechanism of ductile fracture in metals are significant for both engineers and metallurgists in designing against plastic collapse and fracture of structures and workpieces. The avoidance of ductile fracture is of importance in metal forming processes, such as design of the process and die in forging, extrusion and drawing.

Rotary forging is an incremental deformation

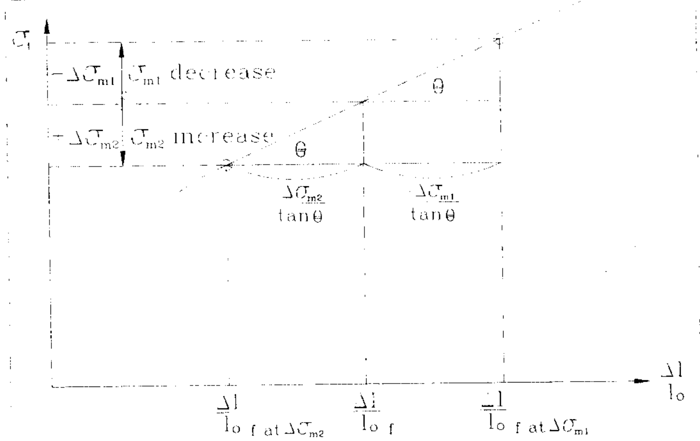

Fig. 1 True stress-elongation curve in uniaxial tensile test with varying mean stress

process in which the deformation is the continuous local deformation instead of the deformation as a whole in conventional forging (Fig. 2), so the process is particularly attactive for producting thin flanges which normally result in appreciable frictional restraint to spread. Nevertheless, while thin circular plates are made by rotary forging, ductile fracture in the certral region of wokpieces shown in Fig. 3 will occur under any given conditions[3,4].

The present investigation is concerned with the application of theory on fracture to the prediction of workability of materials in rotary forging, with special reference to center crack. Experiments on rotary forging were conduted for examining the validity of the new ductile fracture theory.

A. Experimental data

Experiments has been conducted to observe crack in rotary forging for aluminum alloy 6061 and carbon steel (0.45%C) at room temperature.

The experimental conditions were as follows:

(1) Tensile test : Testing was performed at room temperature on an Instron testing machine at a nominal strain rate of 0.03mm/mm/min. Measurements of extension were performed continuously until fracture with an extensometer exhibiting a stain sensitivity of at least 0.0005mm/mm.

(2) Upsetting in rotary forging : Experiments were conducted in the rotary forging press which has been designed and constructed in our laboratory[5]. The forming load is supported by the hemispherical bearing. Pressure-raised oil is supplied for the lubrication of the bearing surface. To reduce required load a slightly larger angle of Upper die of 3 degrees is used. Therefore experiments have been carried out only in case of 3 degrees. The

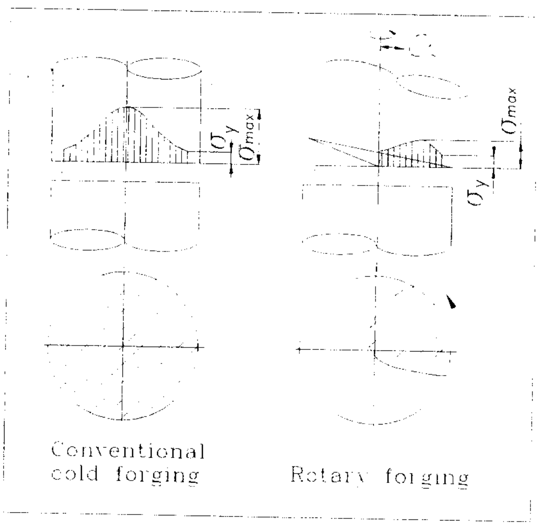

Fig. 2 Principle of rotary forging

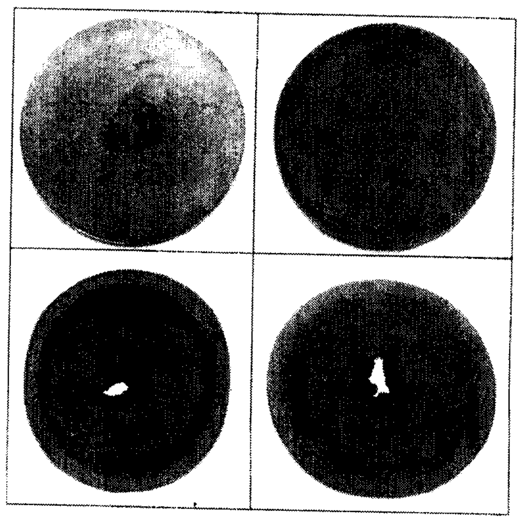

Fig. 3 Samples fractured at center

Table 1 Dimensions and Stree-stain relationship of workpiece

	Height H_0/mm	Diameter D_0/mm	$\bar{\sigma}=A\bar{e}$ (Kg/mm²)
Steel (0.45%C)	10.0	25.0	$\bar{\sigma}=130(\bar{e})^{0.25}$
	15.0	25.0	
Aluminum (A6061)	10.0	25.0	$\bar{\sigma}=68.1(\bar{e})^{0.21}$
	15.0	25.0	

materials were prepared shown in table 1.

(3) Results : Tension test results are shown in table 1 and Fig. 4 and upsetting experiment results are shown in Fig. 6.

B. Computation and results

Using 3-d slab method and plastic hinge model, the stress components in the central part of workpiece were analyzed for the material A6061 and carbon steel(0.45%C). The detailed mechanics were presented in the previous paper[6]. Therefore the mean stress in the central part of workpiece can be obtained from the above analysis.

From the proposed ductile fracture criterion and the tension tests, we can dervied the following relationship.

$$\text{steel}(0.45\%\text{C}) : \left(\frac{\Delta l}{l_o}\right)_{fat\Delta\sigma_m} = \left(\frac{\Delta l}{l_o}\right) + \left(\frac{-1}{\tan\theta}\right)\Delta\sigma_m = 0.28 + \left(\frac{-1}{140}\right)\Delta\sigma_m. \quad (3)$$

$$\text{Al}(\text{A6061}) : \left(\frac{\Delta l}{l_o}\right)_{fat\Delta\sigma_m} = \left(\frac{\Delta l}{l_o}\right)_f + \left(\frac{-1}{\tan\theta}\right)\Delta\sigma_m = 0.14 + \left(\frac{-1}{113}\right)\Delta\sigma_m. \quad (4)$$

Therefore the ductile fracture will occur when the depressive mean stress variations at a point of steel(0.45%C) and Al(A6061) are 39.2, 15.82 and over respectively. The values of parameters of rotary forging at the time when the ductile fracture occurs can be discovered by using the above eqns. and stress analysis as shown in Fig. 5.

Proceeding in a way same to the above method repeatedly, the following relationship on center cracks in the central region can be obtained by approximating the distribution of the theoretical

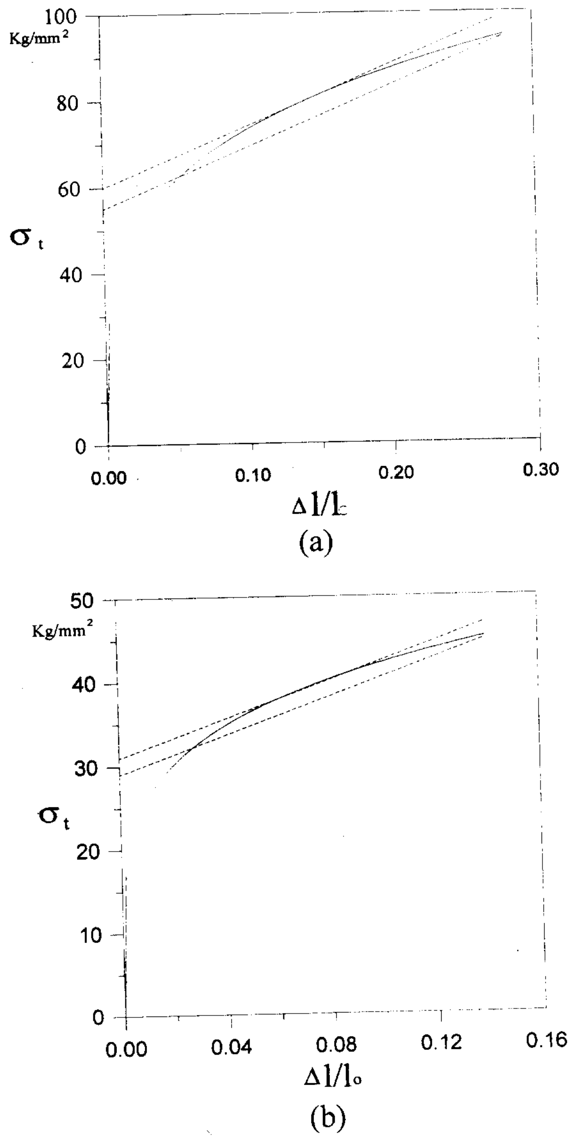

Fig. 4 True stress-elongation curve in uniaxial tensile test (a) steel (0.45%C) and (b) aluminum (A6061)

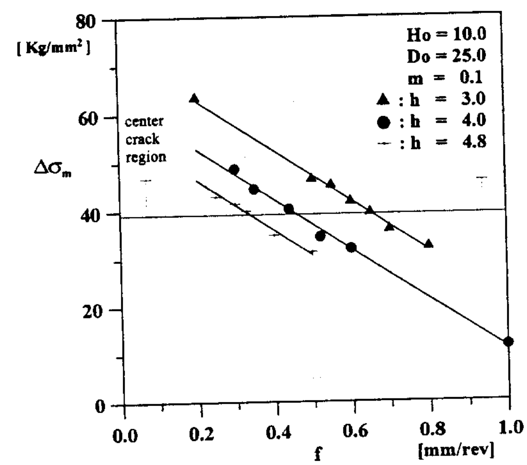

Fig. 5 Relation between $\Delta\sigma_m$ and feeding rate of rocking die per revolution(f) in central region of workpiece, steel(0.45%C)

fracture points to series of continuous curves in rotary forging.

$$\text{steel}(0.45\%C):\ \frac{f}{h}=0.0085\left(\frac{R}{h}\right)^{1.6},\ \alpha=3°,\ m=0.1 \quad (5)$$

$$\text{Al}(A6061):\ \frac{f}{h}=0.011\left(\frac{R}{h}\right)^{1.588},\ \alpha=3°,\ m=0.1 \quad (6)$$

where f is feeding rate of rocking die per revolution, h is current height of workpiece, R is current radius of workpiece, α is inclination angle of upper die and m is friction factor.

The meaning of eqns. (5) and (6) are that center crack occurs when $(f/h)<0.0085(R/h)^{1.6}$ for steel (0.45%C) and $(f/h)<0.011(R/h)^{1.588}$ for Al (A6061), that is, the lower part of the curve represents the center crack region (Fig. 6).

As the result of the theoretical analysis and experimental results about center crack in rotary forging, the following facts are observed.

(1) The height that center crack begins (h) does not depend on the original height of workpiece and the rotational speed.

(2) The height that center crack begins (h) increased with the decreasing of the feeding rate of rocking die per revolution (f) and the radius of workpiece.

In Fig. 6, the calculated criterion on center crack is compared with the experimental data. The calculated results agree fairly well with the experimental ones. It is found that there is good agreement between the theoretical criterion of the center crack and the experimental result. Therefore the ductile fracture limit in the central region of circular plate in rotary forging can be determined by eqn. 2.

Although conclusive validity of the present ductile fracture theory in rotary forging awaits more extensive and systematic experimental investigations, as well as theoretical calculation, the method of computation is available and the approach has been cleared toward complete understanding of ductile fracture in metalworking processes.

4. Conclusion

(1) From the proposed new ductile fracture criterion, the theoretical prediction on center crack in rotary forging is made. The calculated results agree fairly well with the experimental ones.

(2) As the result of thoretical analysis on center

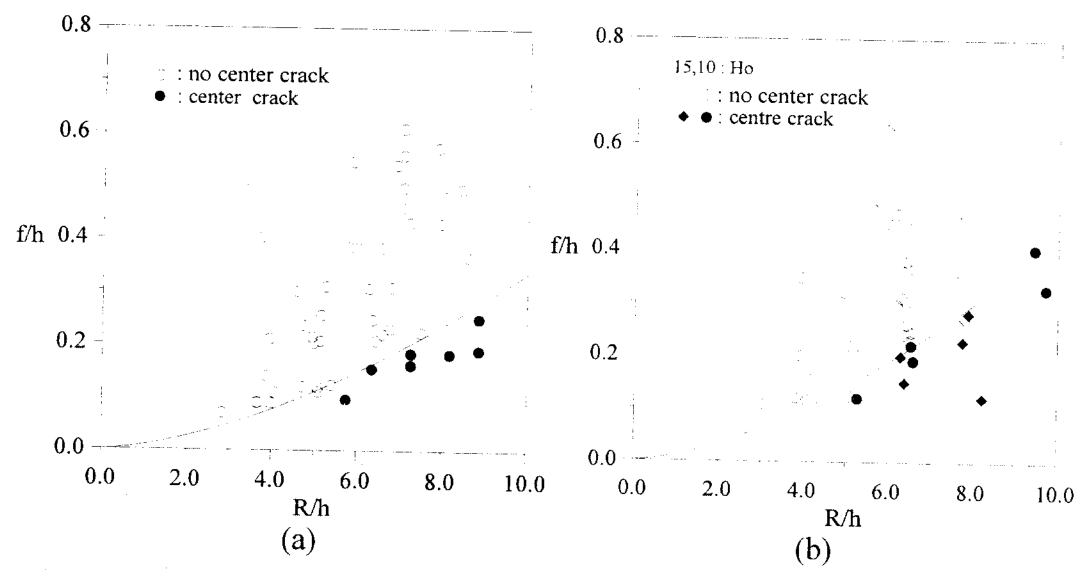

Fig. 6 Comparison between theoretical criterion on center crack and experimental center crack (a) steel (0.45%C) and (b) aluminum (A6061), m=0.1

crack in rotary forging, we can understand the effects of some parameters affecting the center crack in rotary forging.

(3) Therefore the ductile fracture limit in rotary forging can be determined by eqn.(2).

(4) But to verify certainly the validity of the new ductile fracture criterion, the more extensive and systematic experimental investigations have to make steady progress.

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