ICF10 01052PR

DUCTILE FRACTURE IN CYLINDRICAL TUBE BULGING UNDER IMPULSIVE LOADING

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ABSTRACT

The critical hoop strain, $\varepsilon_{\theta c}$, to cause the localized necking is determined experimentally for cylindrical tubes subjected to impulsive, electromagnetic pressure. As the tube is thin-walled and long, it behaves approximately under conditions of plane stress and conditions of plane strain. An approximate formulation of dynamic instability in high-speed expansion of such a tube was developed before in order to predict the forming limit. The analysis indicated that the hoop strain at the occurrence of dynamic instability was in range of n/2 to n for a material with the strain-hardening exponent n in the power law. It is revealed that the critical hoop strain determined experimentally satisfies the following conditions: $n/2 \leqq \varepsilon_{\theta c} \leqq n$.

KEYWORDS

ductile fracture, tube bulging, electromagnetic forming, dynamic instability, aluminum

INTRODUCTION

It is important to clarify the fracture strain at which the workpiece fractures during the plastic forming of materials. As for the ductile fracture of a thin-walled tube subjected to internal pressure, the localization of the deformation – namely, localized necking is ahead of the fracture. Therefore, the condition of the necking formation is a safety standard for the fracture criterion. The necking is generated axially at one spot in the thin-walled and long tube under quasistatic bulging by internal pressure. However, the localized necking prior to the fracture emerged also axially but at eight spots when a tube was subjected to the impulsive, electromagnetic pressure (Tobe et al.,1984). The bulging height of the tube expanded impulsively was higher than that of the tube expanded quasistatically. Dynamic tube expansion is considerably different from quasistatic tube expansion in some aspects.

In this paper the critical hoop strain, $\varepsilon_{\theta c}$, to cause the necking is determined experimentally for the cylindrical tube subjected to impulsive, electromagnetic pressure. As the tube is thin-walled and long, it behaves approximately under conditions of plane stress and conditions of plane strain. The approximate formulation of dynamic instability in high-speed expansion of such a tube was developed before in order to predict the forming limit (Tobe et al.,1984). Karman's criterion for the dynamic tensile critical strain was employed. The analysis indicated that the hoop strain at the occurrence of dynamic instability was in range of n/2 to n for a material with the strain-hardening exponent n in the power law. It is shown that the critical hoop strain $\varepsilon_{\theta c}$ determined experimentally satisfies the following conditions: $n/2 \leqq \varepsilon_{\theta c} \leqq n$.

TESTING MATERIALS

Cylindrical tube specimens of 50 mm in outer diameter, 1mm in thickness and 200 mm long are drawn from commercially pure aluminum (JIS:A1050) and aluminum alloy (JIS:A6063). Tensile test specimen in dumbbell type and compressive test specimen in circular disk type are machined from plates. These plates are 0.75 mm in thickness from the thin-walled tube cut open and followed by flat-rolling. Then all the specimens are annealed at temperature 623 K for 3600 s in an electric furnace. At true strain beyond 0.1 the stress-strain curve determined from tensile test at quasistatic strain-rate was expressed by the power curve relation

$$\sigma = F\varepsilon^n, \qquad (1)$$

where σ is the true stress, ε the true strain, n the strain-hardening exponent and F the strength coefficient. The material constant n and F are shown in Table 1.

Table 1 Material constant F and n in the expression $\sigma = F\varepsilon^n$

	Static tension		Impulsive bulging	
	F [MPa]	n	F [MPa]	n
Aluminum (A1050-o)	124.	0.245	212.	0.23
Aluminum alloy (A6063-o)	150.	0.23	204.	0.20

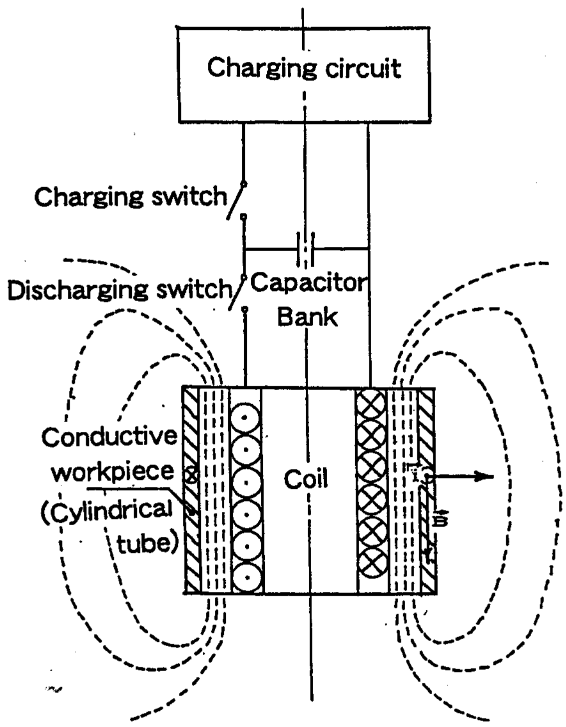

Fig.1 Basic circuit for electromagnetic forming

EXPANSION PROCESS OF TUBE

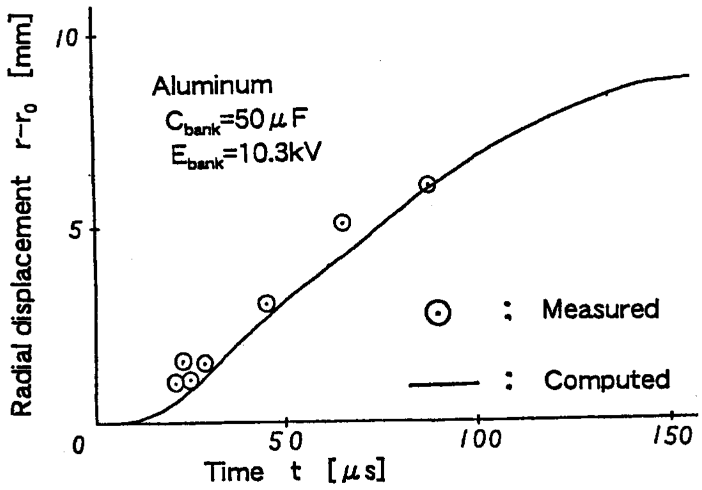

Fig.2 Radial displacement of aluminum tube subjected to electromagnetic pressure.

The dynamic bulging of thin-walled tubes are made use of the electromagnetic metal forming process (Baines et al., 1965-66; Jansen, 1968; Bruno, 1968; Lal, 1972). The basic circuit for electromagnetic forming is shown in Fig.1, in which the energy source is a bank of capacitors, charged to a predetermined voltage. The thin-walled tube of conducting material to be formed is placed over a solenoidal coil which is connected in series with the charged capacitor by means of a discharging switch. On closing the switch, the time-varying primary current in the coil sets up a transient axial magnetic field in the radial air gap and the tube wall, together with a secondary solenoidal current in the workpiece. The interaction of current and magnetic field induces radial body forces in the tube wall, which can be made sufficiently large to deform the workpiece.

The radial movement of the tube wall, $r-r_0$, during the electromagnetic pressure pulse is expressed by the following equation:

$$\frac{d^2r}{dt^2}=\frac{\mu r_i^4}{2\rho r_0 h_0 p^2}\frac{i_1^2}{r^3}-\frac{F}{\rho}\left(\frac{2}{\sqrt{3}}\right)^{n+1}\left(\ln\frac{r}{r_0}\right)^n\frac{1}{r}, \quad (2)$$

where r and r_0 are the current and initial mean radius of the tube, respectively. h_0 and ρ are the initial thickness and density, respectively. t, μ, r_i, i_1 and p denote time, the permeability, the effective radius of coil, the coil current and the axial coil pitch, respectively. Here the hoop stress in the thin-walled tube (the thickness stress $\sigma_r \fallingdotseq 0$) under conditions of plane strain (the axial strain $\varepsilon_z \fallingdotseq 0$) is expressed as the equation: $\sigma_\theta=F(2/\sqrt{3})^{n+1}[\ln(r/r_0)]^n$, since the strain hardening characteristic is assumed to obey the equation, $\sigma_g=F\varepsilon_g^n$, where σ_g and ε_g are the generalized stress and strain, respectively.

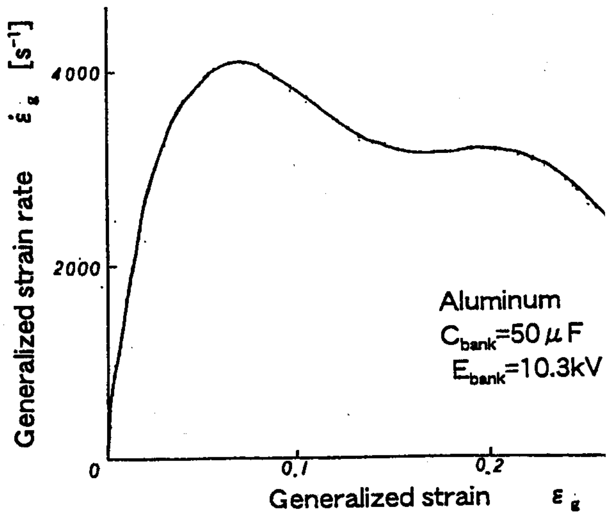

Fig.3 Relation between generalized strain rate and generalized strain for aluminum tube subjected to electromagnetic pressure.

The necking deformation occurred axially in the aluminum tube by applying a bank voltage of 10.3 kV for the capacitor bank of 50 μF. For the aluminum alloy tube such necking occurred by applying 12.7 kV for the capacitor bank of 50 μF. Hereafter the experiments were conducted with these capacitor bank conditions.

The coil current i_1 was measured by integrating the output voltage of Rogowski coil. The radial velocity and the radial displacement of the tube at every moment were determined numerically by integrating equation (2). In Fig. 2 the computed, radial displacement for the aluminum tube is compared with the radial displacement which is measured on the basis of a Hopkinson bar method. This figure shows a similar tendency between the computed curve and the experimental points. The largest cause for the difference between analysis and experiment may be due to the neglecting of strain-rate effects of the tube materials. Therefore the history of hoop strain-rate was computed during the electromagnetic forming. Under conditions of plane strain the generalized strain-rate $\dot{\varepsilon}_g$ is expressed by the following equation : $\dot{\varepsilon}_g=2\dot{\varepsilon}_\theta/\sqrt{3}$. Figure 3 shows the computed relation between generalized strain-rate $\dot{\varepsilon}_g$ and generalized strain ε_g for the aluminum tube during the forming. The maximum strain-rate in this figure reaches 4000 [s^{-1}] during the electromagnetic forming.

MATERIAL PROPERTIES DURING IMPULSIVE FORMING

Since the tube material shows sensitivity to strain-rate, those material properties have to be obtained during electromagnetic forming. Laminated, circular plates which were prepared are compressed within the strain rate range of 10^{-3} to 10^3 s^{-1}. A split Hopkinson pressure bar apparatus (Sato et al., 1988), an oil hydraulic press and a universal testing machine were used for the high strain rate (10^2 to 10^3 s^{-1}), medium strain rate (1 s^{-1}) and low strain rates (10^{-3} s^{-1}) tests, respectively. The flow stress is determined by applying an extrapolation method (Sato et al., 1988) to the above test results in order to eliminate the effect of friction.

For the aluminum tube, the flow stress-strain curves can be evaluated as follows:

$$\sigma = 137.9\varepsilon^{0.24}\left\{\dot{\varepsilon}/8\times10^{-4}\right\}^{0.03}[MPa]. \tag{3}$$

Then a stress-strain curve along an arbitrary strain rate – strain path can be obtained on the basis of equation (3). Therefore, the stress-strain curve for the aluminum tube is determined along the strain rate – strain path, which is shown in Fig.3. Both the stress-strain curves for two kinds of tube during the electromagnetic forming under each condition could be expressed by the power curve equation (1). These material constants n and F are also shown in the column of "impulsive bulging" in Table 1.

CRITICAL HOOP STRAIN

To investigate the distribution of the thickness strain of a tube along the circumferential direction at the middle during the pulse forming, the tube is stopped to deform in its bulging stage by the stopping ring which is shown in Fig. 4. The thickness of the deformed tube is measured at 48 points along its circumference at the middle. The ratio of current thickness h to mean thickness h_m is given against the angle at the circumference for the aluminum tube in Fig. 5, which shows the non-uniform thickness and that the tube has the thinner thickness at eight spots. In Fig. 6 the standard deviation of thickness measured for the aluminum alloy tube is plotted against the hoop strain which is determined by the inner diameter of stopping ring. This figure shows that according as the hoop strain increases the standard deviation increases and necking is generated.

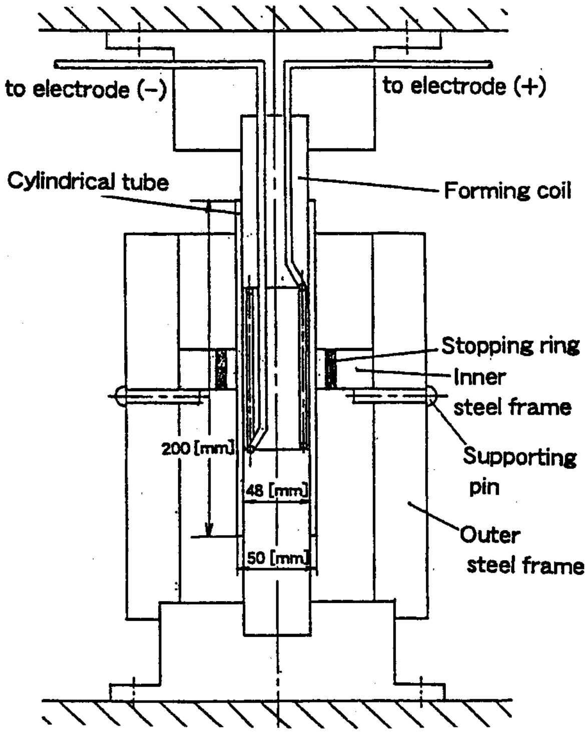

Fig.4 View of forming coil, cylindrical tube and stopping ring with steel frames.

According to close observation of the tubes with various deformations given by the stopping tests, it seemed that the tube surface at the thickness ratio h/h_m under 0.93 became depressed against the surrounding surface. When we made a decision concerning the formation of necking according to this basis, the hoop strain, ε_θ, with necking was the following: $\varepsilon_\theta \geqq 0.13$ for the aluminum tube, and $\varepsilon_\theta \geqq 0.17$ for the aluminum alloy tube, respectively. Therefore, the critical hoop strain, $\varepsilon_{\theta c}$, to cause the necking is 0.13 and 0.17 for the aluminum tube and the aluminum alloy tube, respectively.

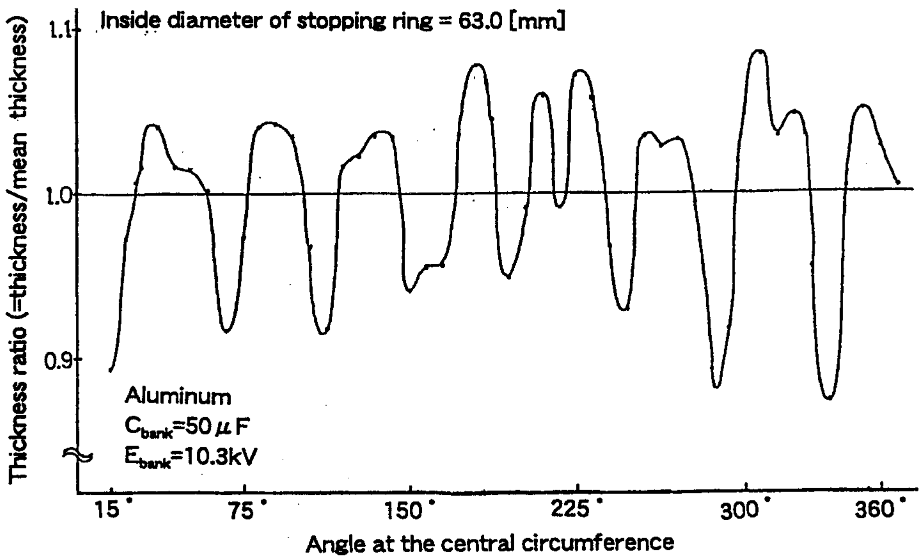

Fig.5 Distribution of thickness ratio along the central circumference. Inside diameter of stopping ring = 63 [mm].

The approximate formulation of dynamic instability in dynamic expansion of a cylindrical tube was developed in order to predict the forming limit (Tobe et al., 1984). The hoop strain, $\varepsilon_{\theta b}$, at the occurrence of dynamic instability was the following:

$$n/2 \leqq \varepsilon_{\theta b} \leqq n. \tag{4}$$

The lower bound of $\varepsilon_{\theta b}$ is the instability strain for the tube subjected to quasi-static internal pressure. It follows that n/2=0.12 for the aluminum tube. On the other hand the upper bound of instability hoop strain is expressed as n=0.23. Then the critical hoop strain $\varepsilon_{\theta c}$ determined experimentally satisfies inequality (4): $0.12 \leqq \varepsilon_{\theta c}=0.13 \leqq 0.23$ for the aluminum tube. In the same way for the aluminum alloy tube, $\varepsilon_{\theta c}$ also satisfies inequality (4): $0.1 \leqq \varepsilon_{\theta c}=0.17 \leqq 0.20$.

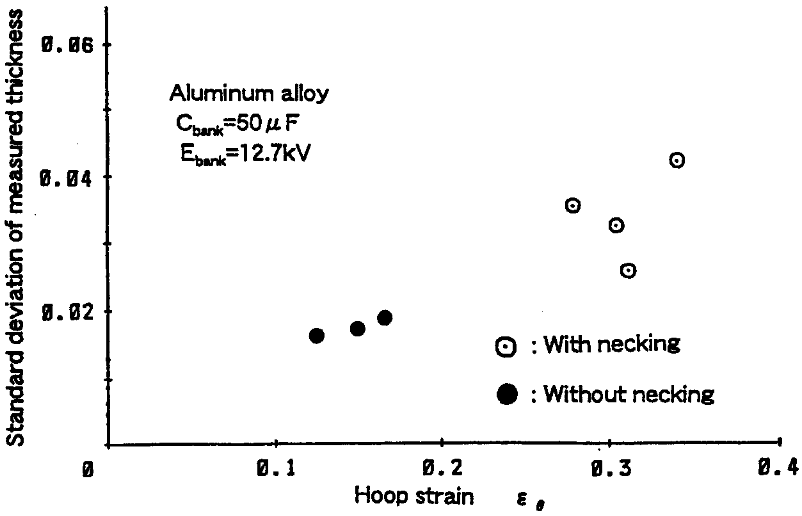

Fig.6 Standard deviation of thickness measured at 48 points along the central circumference against hoop strain for aluminum alloy tube with various deformations.

CONCLUDING REMARKS

In this paper the critical hoop strain, $\varepsilon_{\theta c}$, to cause the necking was determined experimentally for the aluminum and aluminum alloy tubes subjected to electromagnetic pressure. On the other hand the analytical formulation, which was developed before, indicated that the hoop strain at the occurrence of dynamic instability was in range of n/2 to n for a material with the strain-hardening exponent n. It was shown that the critical hoop strain $\varepsilon_{\theta c}$ determined experimentally satisfied inequality (4): $n/2 \leqq \varepsilon_{\theta c} \leqq n$. More accurate estimate of the instability strain is needed, since the instability strain $\varepsilon_{\theta b}$ is in a wide range as shown in inequality (4).

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