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전자장 pulse하의 금속 Cylinder의 팽창에 대한 연구

서 주 하 *

Numerical Analysis of the Expansion of a Metalic Cylinder Under Electormagnetic Pulse

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높은 전압으로 충전된 Capacitor를 순간적으로 원통형 coil에 방전하면 순간적으로 강한 전자장 impluse가 발생한다. 이때 coil를 둘러 싼 금속 tube는 radial 방향의 힘을 얻어 팽창한다. 본 논문은 이때 tube내의 전자장분포와 tube벽의 움직임을 integral equation method를 사용하여 해석하였다.

1. INTRODUCTION

Discharge of a high voltage capacitor bank through a cylinderical forming coil of low impedance produces an intense axial field; if this field is coupled with a cylinderical metal workpiece, intense impulsive forces act on the material. This radial force accelerates the workpiece and causes the plastic deformation of the workpiece if the yield strength is overcome. The coupling occurs by induction and there is no mechanical contact. The coil used must be shaped to conform to the workpiece [1, 2, 3, 4].

This technique is especially suitable for forming or assembling of tubes of high electrical conductivity and of low mechanical strength by compression or expansion using solenoidal coils. For the design of efficient systems of this process, it is im-

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portant to know the behavior of the workpiece during the forming operation. The workpiece changes its geometry significantly during the application of forming pulse. This movement changes the electromagnetic parameters of electrcal circuit, particularly the inductance of the forming coil. The knowledge of the displacement of the moving wall of the workpiece as well as the magnetic pressure pulse as a function of time allows the system designer to match the geometry of the coil.

For this analysis of displacement of the workpiece wall, the developped force in the workpiece must be known. This can be obtained by the knowledge of the magnetic field and the induced current distribution in the workpiece. In this paper, the integral equations method was used for the calculation of the distribution of currents and magnetic fields within the workpiece, and the developped magnetic forces and the movement of workpiece wall were calculated. The calculated results for the case of expansion of a tube were compared with the experimental ones.

2. NUMERICAL ANALYSIS

The magnetic forming system for the expansion of cylinderical workpiece consists of a capacitor bank as energy source, ignitrons as switching device, busbars, forming coil and the workpiece. The cylinderical forming coil can be equivalent electrically to an inductance and resistance in series. Therefore, the magnetic forming circuit is quite closely represented by the equivalent circuit in fig.1 and the discharge current can be discribed ;

$$R(t)\ I(t) + \frac{1}{C(t)} \int I(t)\,dt + \frac{d}{dt}\left(L(t)\ I(t)\right) = 0 \quad (1)$$

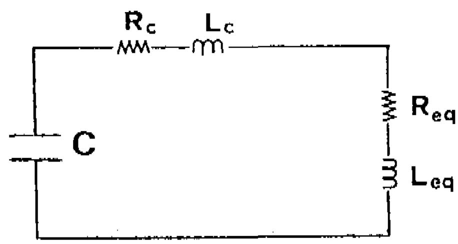


Fig. 1

where

$C[t]$ = total capacity of the circuit
≅ capacity of the storage bank
= constant

$$R(t) = Rc(t) + Req(t)$$

with

R_c is internal resistance of the system

R_{eq} : sum of coil resistance and equivalent resistance of the workpiece at the coil side

and

$$L(t) = Lc(t) + Leq(t)$$

with

L_c is an internal inductance of the system,

L_{eq} : equivalent indctance of coil and workpiece looked at coil side.

The internal resistance and inductance of the system vary with the frequency, but the variation of frequency for an operation is not too much to be able to consider them constant.

For the calculation of the inductance and effective resistance of a system of conductors where the alternative currents are imposed, the knowledge about the current distribution is required. A numberical method for the calculation of the current distribution was developped for estimating inductance and a. c. resistance, based on the integral equations method [5, 6, 7, 8]. The current distribution of the crossection of the forming coil and of a tubular workpiece changes with the frequency and the distance between them. In consequence, R_{eq} [t] and L_{eq} [t] will be changed when the workpiece is plastically deformed. But in the case where radial depth of the crossection of the coil wire is larger then several times of the skin depth and the workpiece is not far from the coil, one can suppose that the currents in the cross section of the wire are uniformly distributed with a skin depth of the side faced the workpiece. For this case, the variation of the resistance and inductance of the coil may be neglected, otherwise , the current distribution of the whole cross section must be considered [9]. The relation [1] with the variation of the parameters is nonlinear, so the time was discretized and the parameters were supposed to be constant within each time interval $\triangle t$. The resistance and the inductance are calculated at each discrete time using the computed distribution of the current with the modified geometry, and the resistane and the inductance are supposed to be constant. The total current in coil discribed in equaton (1) for the nth time interval is

$$I(n\triangle t) = I((n-1)\triangle t)\, e^{-\triangle t/\tau} \sin(\omega(n\triangle t)) \qquad (2)$$

where

$$\tau = \frac{2L((n-1)\triangle t)}{R((n-1)\triangle t)} \quad \text{and}$$

$$\omega = \sqrt{\frac{1}{L((n-1)\triangle t)C} - \frac{1}{\tau^2}}$$

3. MAGNETIC FORCE

The magnetic force on the conductor with the length l carrying a current I being in a magnetic field with the induction B can be obtained by the relation

$$\vec{F} = \vec{I}\,.\,l \wedge \vec{B}$$

Considering an element of volume dv, the volume specific force f becomes to

$$\frac{d\vec{F}}{dU} = \vec{f} = \vec{J} \wedge \vec{B} \qquad (3)$$

where J is the current density.

The eddy currents can be calculated in a conductor under the influence of the known exciting field. Introducing the magnetic vector potential : $\vec{\nabla} \wedge \vec{A} = \vec{B}$

$$\vec{\nabla} \wedge \vec{\nabla} \wedge \vec{A} = -\mu \vec{J} \qquad (4)$$

where μ is the magnetic permeabilty.

The solution of (4) with the Coulomb 's gauge $\nabla \cdot \vec{A} = 0$, is

$$\vec{A}(\underline{r}) = \vec{A}_0(\underline{r}) + \frac{\mu_0}{4\pi} \int_V \frac{\vec{J}(r^1)}{|r - r^1|} dV^1 \qquad (5)$$

where A_0 represents the magnetic vector potential due to the external source and $\underline{r}$, the position vector of a point.

Using

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \vec{\nabla}\phi$$

where ϕ is scalar electric potential

$$\vec{A}(r) = \vec{A}_0(\underline{r}) - \frac{\mu_0}{4\pi\rho} \int_V \frac{1}{|r - r^1|} \frac{\partial \vec{A}(\underline{r}^1)}{\partial t} dV^1 \qquad (6)$$

where ρ is electrical resistivity.

Solving equation (6), the current distribution of eddy current is

$$J = -\frac{1}{\rho} \frac{\partial A}{\partial t} \qquad (7)$$

And B is obtained by

$$\vec{B}(\underline{r}) = \vec{\nabla} \wedge \vec{A} = \vec{\nabla} \wedge \vec{A}_0$$

$$- \vec{\nabla} \wedge \left(\frac{\mu_0}{4\pi\rho} \int_V \frac{\frac{\partial \vec{A}(r^1)}{\partial t}}{|\underline{r} - \underline{r}^1|} dV^1 \right)$$

$$= \vec{B}_0(\underline{r}) - \frac{\mu_0}{4\pi\rho} \int_V \vec{\nabla} \frac{1}{|\underline{r} - \underline{r}^1|} \wedge \frac{\partial \vec{A}(\underline{r}^1)}{\partial t} dV^1 \qquad (8)$$

Supposing that the coil and the work-piece are axisymmetry, the force density at a point within the wokpiece is

$$\vec{f} = \vec{J} \wedge \vec{B}$$

$$= J\varphi \ B_z \hat{r} - J\varphi \ B_r \hat{Z} \qquad (9)$$

where $\hat{r}$ and $\hat{z}$ represent the radial and axial components in the cylinderical coordinate system.

4. DISPLACEMENT OF THE WORK-PIECE WALL

The equation of radial equilibrium for a thin tube expanding plastically under an interal pressure is

$$P_{mag} = \frac{h}{r} \sigma + mh \frac{d^2 r}{dt^2}$$

where σ is stress, h; thickness of workpiece, r; raduis of workpiece and m; mass density.

The first term of right side represents the pressure necessary to deform the cylinder plastically and the second term is the pressure necessary to overcome the inertia of the cylinder wall.

As the dynamic stress-strain relation under varying strain rate conditions, that is the case of magnectic forming, is not possible to obtain. The relation between stress, strain and strain rate may be expressed by

$$\sigma = \sigma_s + f(\dot{\varepsilon}) \qquad (11)$$

where σ_s is quasi-static stress.

For the calculation, authors used a stress-strain relation where the variation with strain rate was not taken account, since the dynamic characteristics on the material used are not obtained easily in the literature. For the first approximation, the quasistatic characteristics is

$$\sigma = \sigma_y + \lambda\varepsilon \qquad (12)$$

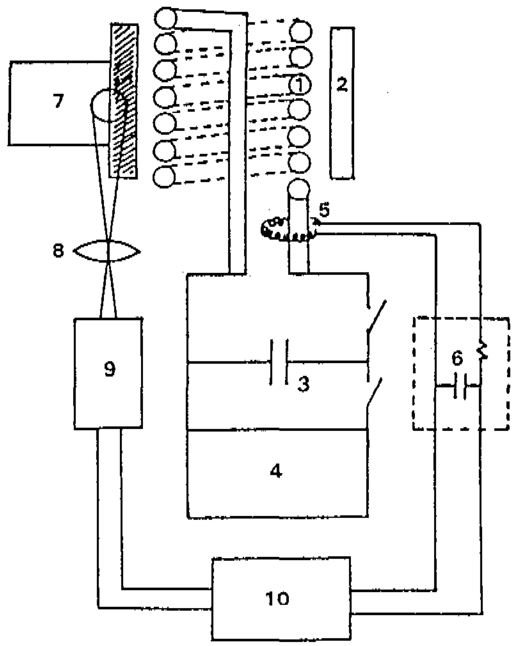
In the case of relatively small strain, the strain may be represrnted by

$$\varepsilon = \frac{\Delta r}{r}$$

hence the relation (12) becomes

$$\sigma = \sigma_y + \lambda \frac{\Delta r}{r} \qquad (13)$$

For simplicity, authors neglected the effect of the temperature on the yield stress of the material as well as the effect of the air resistance at high velocities. Further, it has been assumed that the material is isotropic and the elastic strains are negligible compared to plastic strains.



(1) Coil (6) Intcgrator
(2) Workpiecc (7) Screen
(3) Capacitor bank (8) Lens
(4) Charging circuit and command (9) Opton
(5) Current probe (10) Osciloscope

Fig. 2 Experimental setup

5. COMPARAISON WITH EXPERIMENT

The experimental lay-out for the expansion of tube is consisted of an energy storage bank of 180μ F and a cylinderical coper coil, an aluminum alloy tube of the quality [5754] and the mesure devices. [Fig. 2]

The experiments are carried out without die and the length of coil is chosed to be a little longer than that of tube in order to obtain uniform expansion. As not all of the variables can be conveniently measured, however, the discharge current in the coil was measured using an internal flow probe [10] followed by an R-C integrating circuit. For the measurement of tube wall displacement, an optical system [OPTRON] was used. This system detects the motion of a sharp discontunity in the intensity of light. In order to obtain light-dark interface the tube wall was painted in black and a white screen is used as a back ground.

Capacitor bank

- Maximum Energy 6Kilo-joules
- Capacity 180Micro-farads

Coil [Cu]

- Number of turn 16
- Outer Diameter 49㎜
- Length 76㎜
- Diameter of wire cross section 4㎜
- Electrical Resistivity 17. 7nano-ohm-m

Workpice (tube in 5754

- Immer Diameter 53㎜
- Thickness 1㎜
- Length 70㎜
- Electrical Resistivity 55 nano ohm-m

Table 1

As the internal inductance and resistance of the system [storage bank, busbars and switchs] change with the frequency of discharge current, it is very difficult to define. Authors have used the values obtained by short circuit test.

The alluminium alloy tubes of 1 mm wall thickness were expanded by a discharge from a bank of 180μ F charged to 3. 3 kv, 3, 73 kv ou 4. 15 kv. The calculated and measured results of the expasion of tube under 3. 3 kv [980 J] are illustrated in fig. 3.

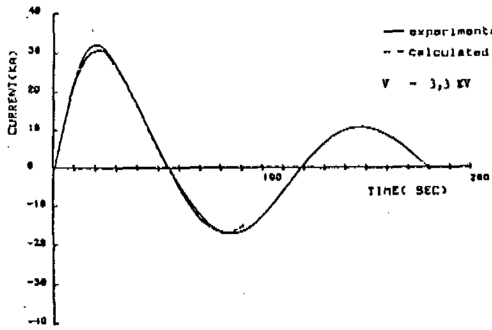


Fig. 3-a Discharga currant

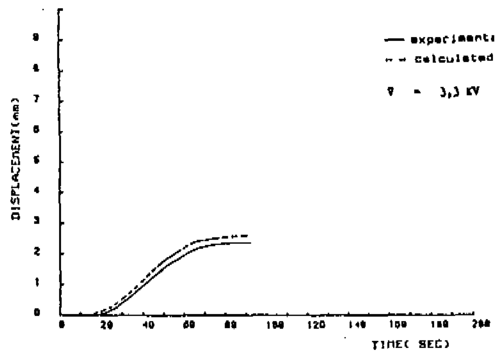


Fig. 3-b Tube wall displacament

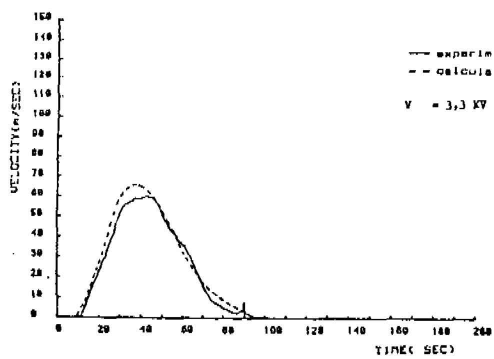


Fig. 3-c Tube wall velocity

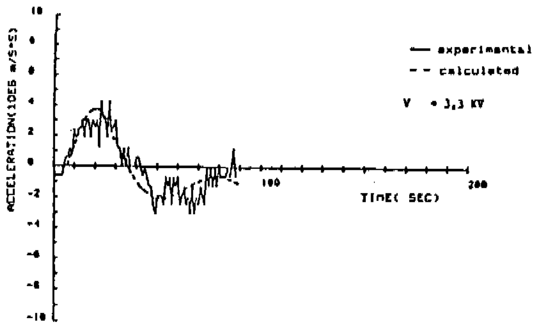


Fig. 3-d Tube wall acceleration

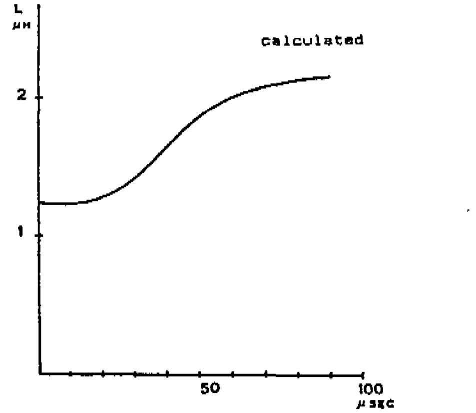


Fig. 4-a Variation of Inductance

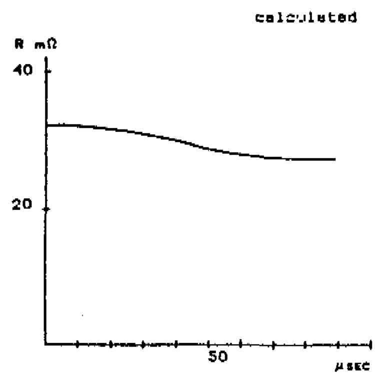


Fig. 4-b Variation of Resistance

The tube started to expand 3 μ secs after closing the switch and the expasion was completed after about 80μ secs. The displacement of tube wall was terminated some μ secs after the second peak of magnetic pressure. The permanent expansion of the radius was between 2.4 and 2.54mm, and the wall displacement velocity attained about 60 m/sec. As soon as the appreciable plastic deformation occurred, the change of geometry affected the inductancd and the resistance, and in consequence, the current, and the magnetic pressure. The Fig. 4-a shows that the inductance increased by about 70% due to the decrease in coupling between coil and the workpiece as the latter moves out. As the total equivalent resistance depends largely on the resistance of coil, the change in resistance [Fig. 4-b] is less marked.

The influence of the strain rate on the certain aluminium alloys is appreciable from the strain rate of 1000 /sec. [11, 12] That is probably a raison why a certain difference of deformation between the results calculated and measured. For the case of the weak energy [Vco = 3.3 kv], $\dot{\varepsilon}_{mas}$ = 2200 /sec, the calculated deformations are slightly larger than those of experiments. [Fig. 3]. If the energy is more important, the difference between the two values is more important. Considering this fact, the mechanical chatacteristics of 5754 may be influenced by the strain-rate. The permanent expansion of tube and the maximum velocity of the displacement are given in the Figs. 5 and 6 in the function of the energy.

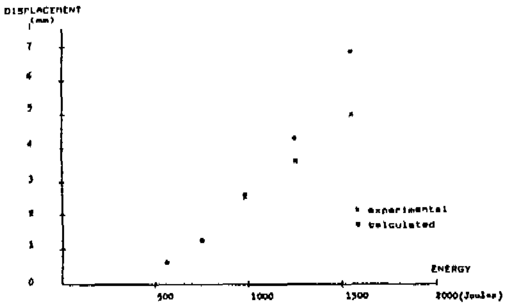


Fig. 5 Radial Expansion as a function of Discharge Energy

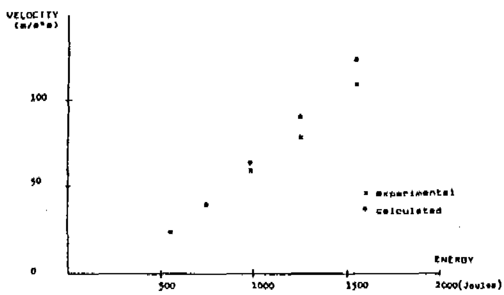


Fig. 6 Maximum Wall Velocity as a Function of Discharge Energy

6. CONCLUSION

The purpose of design of electromagnetic forming tools, it is important to know the relationships between the geometry of the forming tool, the length of the pressure pulse, and the behavior of the workpiece during its plastic deformation. In order to make an attempt at illuminating these relations, the analysis must be effected. The presented analysis of the expansion of a tube by the magnetic pressure gives satisfactory results by comparison with experimental ones. In order to obtain more accurate analysis, the effect of strain rate must be considered.

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