Materials Physics and Mechanics 26 (2016) 81-84 Received: October 2, 2015

DYNAMIC DEFORMATION AND FRACTURE OF THIN METAL RING SAMPLES UNDER MAGNETIC PULSE LOADING

O.K. Zaychenko*, A.A. Lukin, V.A. Morozov

St. Petersburg State University, St. Petersburg, Russia

*e-mail: o.k.zaychenko@gmail.com

Abstract. This paper presents an analysis of the equations describing electromagnetic oscillations in coupled coil and ring circuits. Based on this analysis, an equation had been established that allows determining the ring current, which was calculated for a wide range of capacitor voltages. Two experimental methods for determination of the current and Ampere force in a ring sample, as well as the radial pressure on its internal surface and its circumferential stress were developed and implemented.

1. Introduction

This paper continues the research of H. Zhang and K. Ravi-Chandar [1, 2], as well as our continuation thereof [3,4], by applying it to wider range of deformation rates. The magnetic pulse method for deformation and fracture of thin metal ring samples that has been developed and tested as part of this study is based on the interaction of the currents in a coil and a thin metal ring placed coaxially around it (the Ampere's force law).

2. Analysis of the Equations of the Electromagnetic Oscillations in Coupled Coil and Ring Circuits

Figure 1 shows the loading circuit. This circuit is based on lumped capacitance (C) and inductance (L) elements. The capacity of the circuit's capacitor was 0.5 μF. The circuit's inductor was a five-turn coil with a diameter of 25 mm made of 1 mm copper wire.

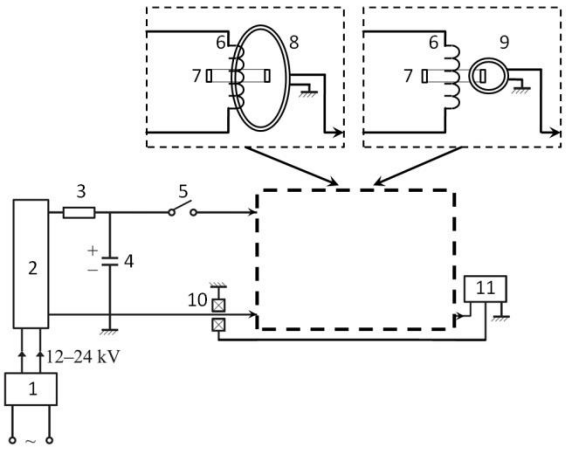


Fig. 1. Sample loading circuit:
1 - autotransformer, 2 - rectifier, 3 - charging resistor, 4 - capacitance, 5 - discharger, 6 - coil, 7 - ring, 8, 9 and 10 - Rogowski coil, 11 - oscilloscope.

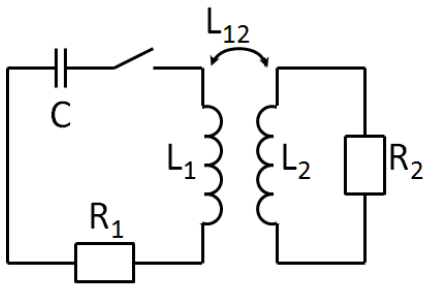


Fig. 2. Equivalent electric diagram.

Figure 2 shows the equivalent electrical diagram for this circuit. This coupled-loop circuit can be described using the following equations:

$$U_c + L_1 \frac{di_1}{dt} + i_1 R_1 + L_{12} \frac{di_2}{dt} = 0, \quad (1)$$

$$L_2 \frac{di_2}{dt} + i_2 R_2 + L_{21} \frac{di_1}{dt} = 0, \quad (2)$$

where U_c is the loaded capacitor voltage, L_1 is the coil inductance, R_1 is the loop resistance, L_2 is the ring inductance, R_2 is the ring resistance, $L_{12} = L_{21}$ is the mutual inductance, and i_1, i_2 are the loop and ring currents, respectively.

Our calculations of the mutual inductance L_{12} show that $L_{12} << L_1$. Considering the aforesaid, equation (1) should be as follows:

$$U_c + L_1 \frac{di_1}{dt} + i_1 R_1 = 0, \quad (3)$$

with the following solution:

$$i_1 = i_{10} e^{-pt} \sin(\omega t + \alpha), \quad (4)$$

where $i_{10} = \frac{U_C}{L_1 \omega}$, $\omega = \sqrt{\omega_0^2 - p^2}$, $\omega_0 = \frac{1}{\sqrt{L_1 C}}$, $p = \frac{R_1}{2L_1}$.

Equation (2) has the following solution:

$$i_2 = A e^{-pt} \sin \omega t + B e^{-pt} \cos \omega t, \quad (5)$$

where $A = i_{10} L_{12} \frac{-L_2(p^2 + \omega^2) + R_2 p}{(R_2 - L_2 p)^2 + \omega^2 L_2^2}$, $B = -i_{10} L_{12} \frac{\omega R_2}{(R_2 - L_2 p)^2 + \omega^2 L_2^2}$.

3. Experimental Procedure and Results

The experiments were performed using a GKVI-300 high-voltage pulse generator, which allows generating voltage pulses with amplitudes of 10–300 kV.

The period of the current from a charging device flowing through the coil with a coaxially attached ring was 5.5 - 7.5 μs.

The experiments were conducted on aluminum and copper foil rings with a thickness of 0.015 mm and widths of 0.8 to 5.0 mm.

The experiments involved measuring the current in the coil using a Rogowski coil (see item 10 in Fig. 1), as well as in the ring using two different methods (Fig. 3). The first method consisted in measuring the magnetic induction in the five coil loops using a Rogowski coil (see item 8 in Fig. 1), both with and without a ring attached to the coil. By the magnetic induction difference between these two configurations the ring current was defined. The second method consisted in measuring the ring current directly using a Rogowski coil (see item 9 in Fig. 1).

The above graph demonstrates that: (a) there is a linear dependence between the ring current and capacitor voltage, and (b) increasing the ring width causes the ring current to increase proportionally up to the coil current value. Figure 4 shows the oscilloscope patterns of the coil and ring currents for a 1.5 mm wide copper ring, as measured experimentally and calculated using equation (5). Similar oscilloscope patterns were obtained for 0.8 and 3.0 mm copper rings, as well as 3.0 and 5.0 mm aluminum rings.

The forces (F(t)) acting on a ring were described in detail in paper [5].

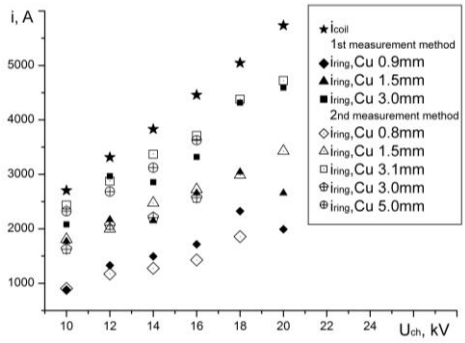


Fig. 3. Dependence of ring current on capacitor voltage for aluminum and copper rings of different widths.

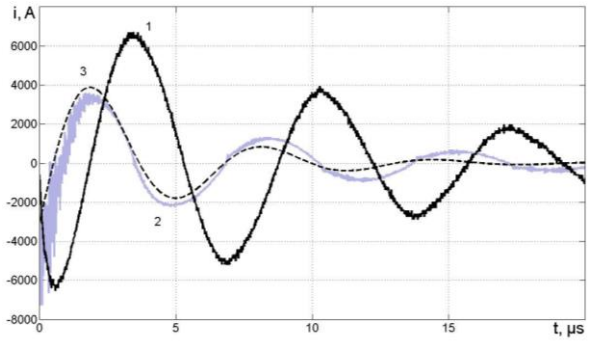


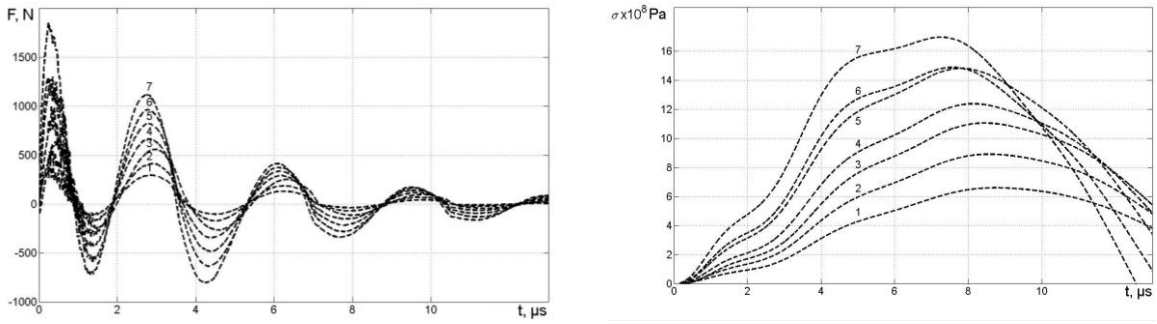
Fig. 4. Oscilloscope patterns for the coil current (1), as well as the measured (2) and calculated (3) ring current.

The distributed load acting on the inner surface of the ring $q(t) = F(t)/c$,wherein c - the width of the ring.

The circumferential stress in a ring was calculated using equation [5]:

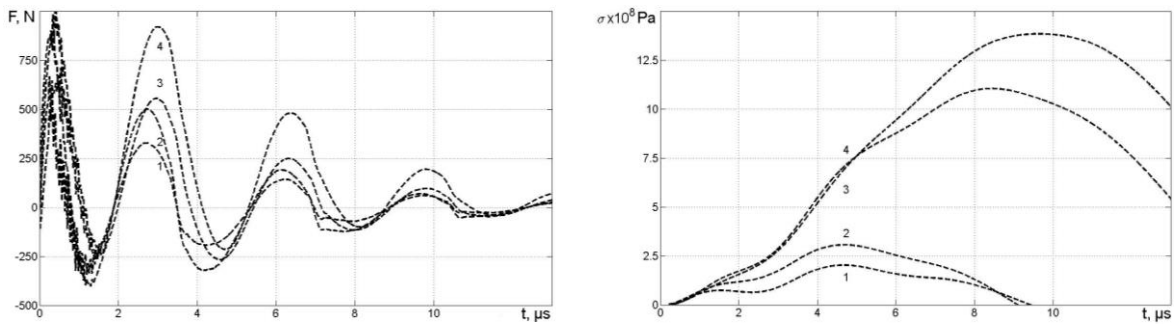
$$\sigma(t) = \frac{\partial \sigma}{\partial t}\Big|_{t=0} \cdot \frac{1}{\omega} Sin\,\omega t + \omega \frac{R_0}{h} \int_0^t q(\tau)\, Sin\,\omega(t-\tau) d\tau. \qquad (7)$$

The values $F(t)$ and $\sigma(t)$ were calculated for aluminum and copper rings of different widths at different capacitor voltages, i.e. at different applied energies. As an example, Fig. 5 shows the dependence of the force (a) and circumferential stress (b) on the capacitor voltage for a 1.5 mm wide copper ring. The graphs in Fig. 6 show the values $F(t)$ and $\sigma(t)$ for different materials (aluminum and copper) for the capacitor energy E = 49 J.



a b

Fig. 5. Dependence of the force $F(t)$ (a) and circumferential stress $\sigma(t)$ (b) on the capacitor energy (1 — 25 J, 2 — 36 J, 3 — 49 J, 4 — 64 J, 5 — 81 J, 6 — 100 J, 7 — 121 J).



a b

Fig. 6. Force $F(t)$ (a) and circumferential stress $\sigma(t)$ (b) calculated for different ring materials and widths (1 — Al, 3.0 mm; 2 — Al, 5.0 mm; 3 — Cu, 1.5 mm; 4 — Cu, 3.1 mm).

The dependence graphs in Fig. 5 and 6 demonstrate the following: 1) Increasing the capacitor energy results in increasing amplitudes of F(t) and σ(t); 2) increasing the ring width (for both aluminum and copper rings) results in increasing F(t) and σ(t) values; 3) aluminum rings have lower amplitudes than copper ones. The latter two conclusions can be explained by the ring resistance decreasing with the increase of the ring width, and, as a consequence, the increase of the ring current. But most importantly that the circumferential stress σ in contrast to the force F is not pulsed. This is a fairly smooth function (see. Fig. 5b, 6b). This circumstance is due to the fact that the inertia of the ring smoothes fluctuations. Identified as a result of the calculations, these particular of ring samples dynamic deformation were previously found experimentally [5]. Analysis of calculated hoop stress changes allow to predict at which period of the current in the ring destruction is possible.

4. Summary

1. This paper presents an analysis of the equations describing electromagnetic oscillations in coupled coil and ring circuits, which allows calculating the ring current.
2. Two experimental methods for determining the ring current were developed and implemented.
3. A comparison of the measured and calculated ring current values was made.
4. Based on the coil and ring currents measured for a wide range of capacitor voltages, two different materials (aluminum and copper) and different ring widths, the dependences of the force acting on a ring and its circumferential stress on the capacitor energy were determined.
5. The obtained results allow assessing the deformation and strength parameters of the above two materials within a wide range of energy parameters.

References

[1] H. Zhang, K. Ravi-Chandar // *International Journal of Fracture* **142** (2006) 183.
[2] H. Zhang, K. Ravi-Chandar // *International Journal of Fracture* **150** (2008) 3.
[3] V.A. Morozov, Y.V. Petrov, A.A. Lukin, V.M. Katz, A.G. Udovik, S.A. Atroshenko, G.D. Fedorovsky // *Reports of the Academy of Sciences* **439(6)** (2011) 761.
[4] A.A. Lukin, N.F. Morozov, V.A. Morozov, Y.V. Petrov // *Procedia Materials Science* **3** (2014) 686.
[5] V.A. Morozov, Y.V. Petrov, A.A. Lukin, A.G. Udovik, S.A. Atroshenko, D.A. Gribanov // *Technical Physics* **84(9)** (2014) 78.