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Longitudinal magnet forces?

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The Ampere electrodynamics of metallic conductors and experiments supporting it predict that the interaction of a current-carrying wire with its own magnetic field should produce longitudinal mechanical forces in the conductor, existing in addition to the transverse Lorentz forces. The longitudinal forces should stretch the conductor and have been referred to as Ampere tension. In 1964 it was discovered that a current pulse would break a straight copper wire into many fragments without visible melting. A metallurgical examination of the pieces confirmed that the metal parted in the solid state. The same observation has now been made with aluminum wires. In the latest experiments the wire was bent into a semicircle and arc-connected to a capacitor discharge circuit. The arc connections ruled out rupture by Lorentz hoop tension and indicated that longitudinal forces may also arise in circular magnet windings. Explanations of wire fragmentation by thermal shock, longitudinal stress waves, Lorentz pinch-off, bending stresses, and material defects have been considered and found unconvincing. Computed Ampere tensions would be sufficient to fracture hot wires. The Ampere tension would double the hoop tension normally expected in dipole magnets. This should be borne in mind in the design of large dipole magnets contemplated for MHD power generators and railgun accelerators.

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I. INTRODUCTION

Since the beginning of electromagnetism in 1820 there have been theories and experiments purporting to show that a current-carrying wire situated in its own magnetic field is subject not only to transverse Lorentz forces but also a set of longitudinal forces. The latter are not electromotive forces which would cause current flow, but mechanical forces attached to the metal lattice and tending to stretch the wire. At liquid-solid conductor interfaces, the longitudinal force makes liquid metal stream away from the interface.[1] Seventy years ago Hering[2] was able to harness this phenomenon for the electromagnetic pumping of liquid metals without using an external magnet. Most longitudinal force experiments have relied on liquid mercury links with which forces of the order of 10–20 g could be measured with a balance.

Tensions of this order of magnitude are insufficient to set up observable strain in conductors of thermally adequate size. The existence of longitudinal forces in solid conductors therefore remained a matter of speculation until, in 1964, Nasilowski[3] found that a large current pulse of several thousand ampere would shatter a 1-mm-diameter, straight copper wire of 1.5 m length into about 100 pieces, varying in length from 0.3 to 3.0 cm, with unmistakable signs of tensile frature in the solid state. He was studying the rupture of fuse wires and particularly the question of why fuses break up almost simultaneously into a large number of pieces when it is known that the temperature along the wire is remarkably uniform.

Ampere[4] carried out an experiment to demonstrate the existence of longitudinal forces. This involved a copper hairpin floating on liquid mercury.[1] It has frequently been argued[5] that the motive forces on the hairpin were not longitudinal forces in the legs, as Ampere maintained, but transverse forces on the hairpin bend. These Lorentz forces have their reaction in the field (not on matter), where electromagnetic mass is supposed to be accelerated to conserve momentum. Pappas[6] has recently shown that the energy that would have to be deposited (radiated) into the field for momentum to be conserved in the hairpin experiment requires a much larger current than has been observed to flow in the circuit.

II. FRAGMENTATION OF ALUMINUM WIRE SEMICIRCLES

An 8-μF high-voltage capacitor bank was discharged through a 1000-μH inductor to produce exponentially decaying oscillatory current pulses up to 10-kA amplitude and ringing down at 2000 Hz over a period of 5–10 ms. The discharge currents were passed through a 1.2-mm-diameter, 99% pure aluminum wire bent into the shape of a semicircle. This shape was chosen to determine if longitudinal forces might be found in magnet windings. As shown in Fig. 1, the

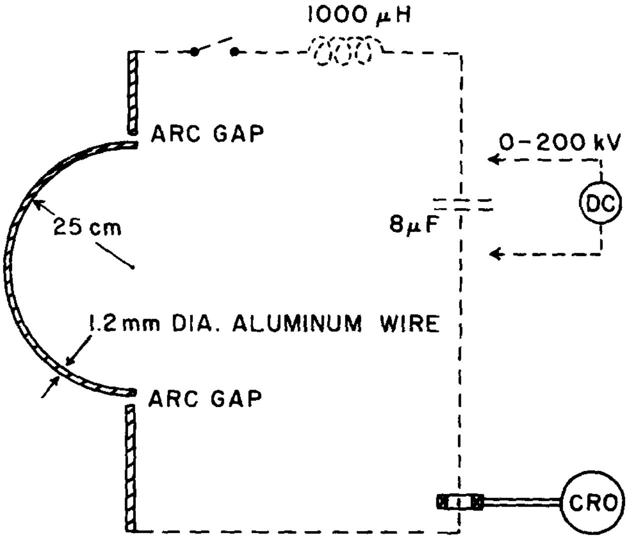

FIG. 1. Wire fragmentation experiment.

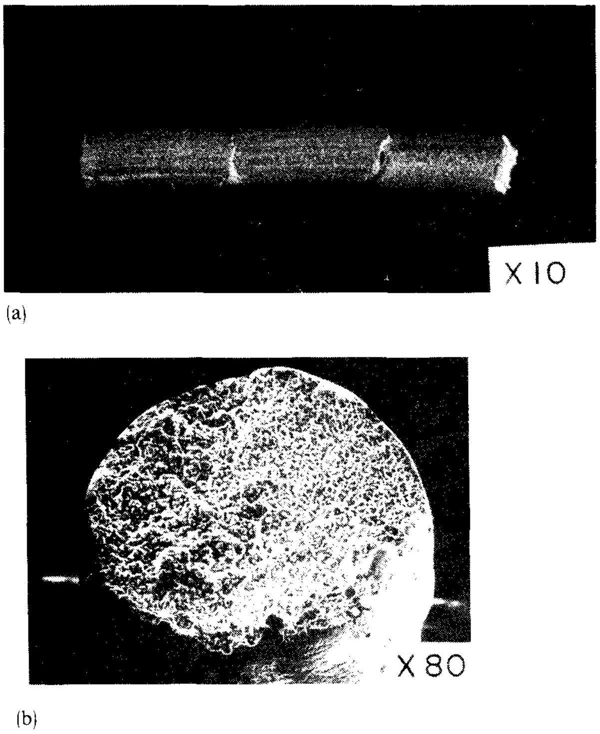

FIG. 2. (a) Photograph of aluminum wire fragments. (b) Scanning electron micrograph of fracture face.

wire semicircle of 25 cm radius was suspended in a vertical plane, leaving 1-cm-long arc gaps to connect it to the terminals of the discharge circuit. The purpose of the arc gaps was twofold. First, they allowed distortion-free thermal expansion. Secondly, assuming that an electric arc in air has no tensile strength, they virtually eliminated the hoop tension which would otherwise have been set up by the transverse Lorentz forces.

The following procedure was adopted. The capacitor bank was charged to 50 kV and then discharged through the inductor and the wire by closing a mechanical switch. This would heat the wire but did not break it. Oscillograms of the discharge current were recorded. They gave the maximum current amplitude and showed the exponential damping. After the wire had cooled back to room temperature, the experiment was repeated with 52 kV and subsequently at 2-kV increments. At 62 kV and a peak current of approximately 6000 A the wire would fracture into two or three pieces. A certain amount of melting could always be found on the arc-gap ends but none could be seen at the fracture faces.

After the first breaks, a new semicircular wire was mounted in place and the discharge experiment was repeated with a further 2-kV voltage increment. This produced a greater number of wire fragments. In this way the fragmentation process could be intensified until, at 68 kV and a peak current of 6600 A, the wire would break into 30 to 50 pieces. A further increase in discharge current would produce visible melting in various places along the wire, thereby destroying the tensile fracture evidence.

Figure 2 shows photographs of wire fragments obtained in this latest series of experiments. The fracture faces were examined with optical and electron scanning microscopes. This left little doubt that tensile fracture had taken place in the solid state.

III. WILL DIPOLE MAGNETS BE SUBJECT TO LONGITUDINAL FORCES?

It seems likely that the tensile forces which fractured the wire semicircles will also be present in dipole magnets subjected to current pulses. The number of turns in the winding should make little difference, so long as the winding width is very much smaller than the winding length. But at present we have no proof that the same forces would arise in a superconducting winding carrying steady currents equal to the pulse ampltiude. We must consider the possibility that the longitudinal forces are not Ampere tension but a secondary effect of the impulsive nature of the current. Five such effects have been mentioned since Nasilowski's discovery of wire fragmentation. Two are associated with the pinch force, the third with thermal shock, and the remaining two with wire bending and defects.

First we look at pinch constriction and rupture as observed in horizontal liquid metal conductors.[2] This is always preceded by a V-shaped depression in the liquid level. But the wires broke without the formation of necks of reduced diameter. This eliminates pinch-off as the cause of wire fragmentation.

The second effect concerns longitudinal stress vibrations initiated by relaxation from a pinch pulse. Nasilowski employed a unidirectional current pulse. The radial pinch was not removed from his wire until the current ceased to flow. Relaxation after pinch removal could have set up travelling stress waves leading to tensile failure. With the aid of voltage drop measurements Nasilowski proved, however, that the wire breaks occurred well before the end of his 20-ms pulse. Hence Nasilowski's results cannot be explained with travelling longitudinal stress waves.

For two fleeting moments in each of the 2000 Hz current cycles of the MIT experiment the radial pinch force fell to zero. Using Northrup's theory of the pinch effect,[7] the maximum longitudinal force trying to extrude the wire was calculated to be 245 g. An extremely fast relaxation mechanism could possibly convert this to tension and magnify it by multiple reflections of the stress wave. The velocity of sound in aluminum is 5100 m/s at 20 °C and less at elevated temperatures. This appears to be inadequate to give rise to multiple reflections in a 1-m-long wire, but in the case of the MIT experiments the possibility of longitudinal stress wave fractures cannot be ruled out altogether.

A quantitative analysis of tension along the wire axis, and due to transverse and longitudinal forces, is being reported elsewhere.[8] By definition, the transverse forces have no tangential component which could accumulate tensile stress along the wire axis. They do, however, set up bending stresses which tend to straighten the wire and have a tensile component associated with them. For bending to assume significant proportions the wire has to deform. This is largely prevented by inertial confinement for the brief period in which the electromagnetic forces are active. But even if large bending deformations did occur, it would still seem unlikely that the highly ductile, 99%-pure aluminum wire could be shattered in many pieces.

Material defects, as for example radial cracks and inclusions of foreign matter, could be the cause of local overheating and premature fracture in bending or tension. No defects of this kind have been found on the series of wire samples subjected to fragmentation. Furthermore, none of the microscopic examinations of fracture faces revealed the presence of prior material defects. The repeatability of the experiments and the great number of fractures that have been regularly produced also cast doubt on any explanation of wire fragmentation that invokes material defects.

On the basis of the present state of knowledge it seems likely that wire fragmentation is the result of longitudinal electrodynamic forces. They would be found in pulse magnets as well as steady current magnets. Ampere tension[8,9] does furnish a plausible quantitative explanation. How Ampere's force law may be applied to metallic circuits has been discussed relative to railgun accelerators.[10] It will be appreciated that the railgun circuit is in fact a pulsed dipole magnet. For the MIT wire fragmentation experiments the Ampere force law predicted tensile forces of the order of 3 kg. Ignoring inertia, this would have been sufficient to rupture the wires at temperatures below 400 °C.

Ampere tension would play a minor role in solenoid magnets because the hoop tension in any individual turn is then largely the result of Lorentz forces generated by the currents in adjacent turns. In dipole magnets the Ampere tension would approximately double the hoop tension resulting from the Lorentz force formula.

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