Reprinted from:
THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 43, NUMBER 5 MAY 1972

Method for Shock Wave Investigation of Magnetic Material*

D. E. GRADY†
Washington State University, Pullman, Washington 99163

(Received 13 September 1971; and in final form, 16 February 1972)

An experimental method developed for investigation of shock induced demagnetization in yttrium iron garnet is reported. The method was found reliable and quite easy to implement. It has the potential of being a useful experimental tool for further investigation of magnetic properties in shock wave studies.

INTRODUCTION

During the course of an investigation of shock induced demagnetization[1] in yttrium iron garnet, an experimental method capable of creating the induced demagnetization and performing the necessary magnetic measurements was developed. The technique was designed for use in conjunction with a gas gun.[2] Subsequent use of the method found it successful and easy to implement. It is believed that the technique could be quite readily used in impact studies for the investigation of this and other magnetic and magnetostructural properties of material. The purpose of this report is to present the details and analysis required for use of this method.

When magnetic material is subject to a strong shock wave and at the same time biased by an external magnetic field applied parallel to the shock front, a reduction in magnetization is observed. By this method shock waves are used to study the magnetic behavior of materials subject to extreme states of stress. In the present work demagnetization is produced by the mechanism of shock induced anisotropy.[1,3,4] Shock induced anisotropy is best understood by considering an infinite half-space of ferromagnetic material contained in the region $x>0$. Planar impact at the interface $x=0$ creates a plane shock wave propagating in the positive x direction. This creates in the region behind the shock wave an infinite slab of ferromagnetic material subject to a state of uniform uniaxial strain. During and following shock initiation, the ferromagnetic material is subject to a transverse magnetic field H_e sufficient to induce magnetic saturation in the material in front of the propagating shock wave. Behind the shock wave a reduction in magnetization occurs. This is a consequence of the magnetoelastic properties of the material which provide an axis of easy magnetization along the direction of shock propagation.

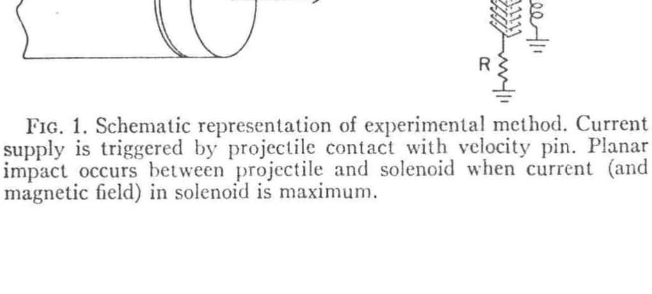

FIG. 1. Schematic representation of experimental method. Current supply is triggered by projectile contact with velocity pin. Planar impact occurs between projectile and solenoid when current (and magnetic field) in solenoid is maximum.

In this work the experimental effort was focused on creating the required state of strain and applied field and measuring the subsequent demagnetization.

A schematic representation of the experimental procedure is shown in Fig. 1. Briefly, the experimental sequence is as follows. A projectile, traveling at velocity V, triggers a current supply consisting of a large capacitance C charged to a voltage $\mathcal{E}_0$. The subsequent current produces a magnetic field in the solenoid which reaches a maximum when the projectile impacts the target. This rectangular solenoid is a single layer of copper ribbon which encloses the experimental sample of YIG. It is mounted in a target holder with one plane face oriented parallel to the projectile face. The impact produces a shock wave which propagates through the solenoid and into the YIG sample. This sample, initially in magnetic saturation, is demagnetized by the shock wave. The demagnetization develops an emf across a pickup coil which is recorded on the monitoring oscilloscopes. The magnetic state of the material behind the shock front is determined from these demagnetization records.

Pulsed solenoids for producing high magnetic fields are discussed elsewhere. Of interest in the present work are means of maintaining this field constant during solenoid collapse and shock demagnetization and passage of a shock wave through the solenoid with minimal deteriorating effect on the wave. Methods for accomplishing this are reported. Analysis of the shock demagnetization is determined in terms of relevant shock parameters.

This article is presented in the following order. In Sec. I operation of the current supply is explained. In Sec. II solenoid and target construction relevant to shock wave experimentation is reported. Section III is concerned with strain wave application. The demagnetization analysis is presented in Sec. IV. In Sec. V limits of the experimental method are considered in terms of shock strength and magnetic field strength. A further application of the experimental method is suggested.

I. OPERATION OF CURRENT SUPPLY

The following operational description will refer primarily to the schematic of the current supply and target circuitry in Fig. 2. Initially the large electrolytic capacitor C is charged to a predetermined voltage $\mathcal{E}_0$. Prior to impact the projectile triggers the current supply as illustrated in Fig. 1. The subsequent discharge of capacitor C develops a current in the solenoid. The form of this current pulse is given by the equation[5]

$$I=(\mathcal{E}_0/\omega L)\exp(-\beta t)\sinh\omega t, \tag{1}$$

where

$$\beta=R/2L$$

and

$$\omega=(R^2/4L^2)-1/LC.$$

The voltage $\mathcal{E}_0$ and the resistance R are preadjusted to obtain a maximum current I_m at a time t_m. R is the dc resistance of the components in the discharge circuit. The time t_m is adjusted to correspond with the arrival of the projectile at the impact surface. The values of $\mathcal{E}_0$ and R are selected from calibration curves obtained from the relation

$$t_m=(1/\omega)\tanh^{-1}(\omega/\beta). \tag{2}$$

At t_m, the current, and, hence, the magnetic field, are quasistationary and remain so for the duration of the experimental measurement (approximately 200 nsec).

The inductor L is an integral part of the experimental design. It is a major component in determining the risetime of the current pulse. More important, the ballast property of the inductor maintains the current and, therefore, the applied magnetic field constant for the duration of the experimental measurement. There are several effects which attempt to change the current. First, passage of a shock wave through the solenoid accelerates the forward face, creating an effective solenoid collapse. Magnetic forces are generated which attempt to conserve the flux in the closing solenoid area and thus increase the magnetic field. Second, when the stress wave traverses the magnetic sample, a large flux reduction occurs during shock demagnetization. The response of the circuit is to attempt to compensate for this flux change. In both cases, it is the function of the inductor L to maintain the current constant. About 0.25–0.5 mH inductors have been found sufficient for this purpose. It should be mentioned that this inductor is located within a few centimeters of the solenoid since its ballast property must be realized within nanoseconds. To locate this inductor in the current supply would create coaxial cable reflections and nullify its stabilizing property.

There is a 1000 Ω resistor paralleling the solenoid to ground. This resistor carries several percent of the total

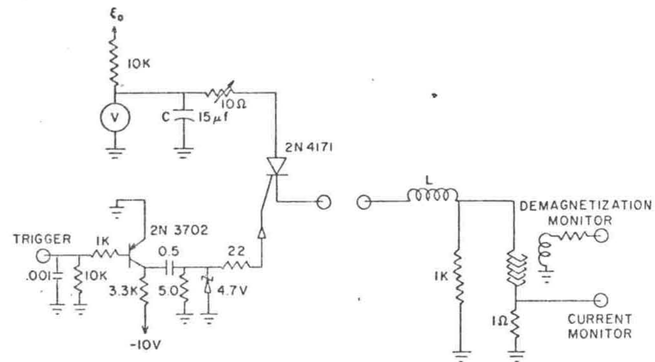

FIG. 2. Current supply and target circuit.

current and, with the solenoid, has an L/R time sufficient to damp out ringing due to the finite stray capacitance of the solenoid windings. The current through the solenoid is monitored by recording the voltage across a precision noninductive 1 Ω resistor in series with the solenoid.

II. EXPERIMENTAL DESIGN

The magnetic samples used in the present work were rectangular slabs of polycrystalline yttrium iron garnet.[6] The dimensions were 0.1×1.0×5.0 cm. The width to depth ratio was chosen to minimize lateral relief wave effects while the length to width ratio was chosen to minimize demagnetizing fields. The sample is positioned with its long dimension along the magnetic field, and the slab face is oriented parallel to the impact surface. A cross section of the solenoid assembly is shown in Fig. 3. Either Lucite or aluminum oxide was used for material on the impact surface. Lucite was used for the solenoid interior. The solenoid windings were constructed of 0.025×0.38 mm OFHC copper ribbon.[7] Usually between 12 and 20 turns per centimeter were used. The solenoid constitutes about 6–9 Ω of dc resistance, a factor which must be considered in the total circuit design. A standard lathe, set in the thread cutting mode, was found to provide an efficient and versatile means for winding a very smooth and regular solenoid.

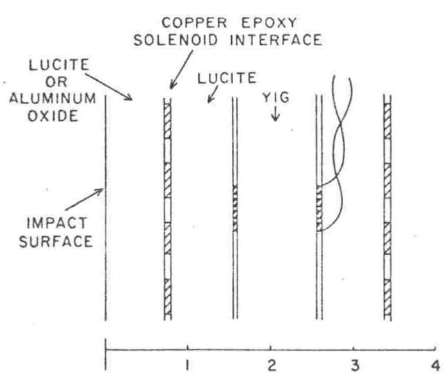

FIG. 3. Cutaway cross section of solenoid. Exhibits approximate dimensions and construction of solenoid.

Although the shock wave propagation distance through Lucite must be kept to a minimum because of Lucite's deteriorating effect on the shock wave rise time,[8] the magnetic sample must be located far enough away from the solenoid face to avoid the ripple effect in the magnetic field produced by the periodicity of the solenoid windings. This ripple effect can be shown to reduce to $1/e$ in a distance

$$y_0 = a/2\pi, \tag{3}$$

where a is the period of the grid.[9]

The pickup coil consists of 10 turns of fine manganin ribbon wound closely around the specimen center as indicated in Fig. 3. The active recording region, defined by the face of the pickup coil, is about 1 cm^2. Manganin ribbon was originally chosen for the pickup coil because of its distributed resistance. It was thought that this resistance might tend to damp parasitic oscillations in the pickup circuit. No attempt has been made to test the merit of this precaution. The pressure dependence of the resistance is negligible for this experimental configuration. A twisted pair of insulated copper wires is solder connected to the pickup coil immediately behind the YIG sample and brought out the end of the solenoid. This twisted pair and connections are not disturbed by the stress wave during the recording time. The solenoid and its associated electrical components and ballast inductor are mounted in a target assembly which is completely potted in epoxy.

III. APPLICATION OF STRAIN FIELD

The target assembly (Fig. 3) is subject to planar impact by the projectile. The subsequent shock wave propagates through the solenoid face and into the magnetic material creating, behind the shock wave, a state of uniaxial strain. This state of strain in the magnetic material is determined from the measured projectile velocity and the known equations of state of the projectile material, intermediate material, and magnetic material. The projectile face should be an insulating material since metal in motion will disturb the magnetic flux in the vicinity of the solenoid. This can seriously perturb the demagnetization measurement.

There are several problems associated with propagating a planar shock wave through the periodic grid defined by the front surface of the solenoid. First, the copper–epoxy interface is a region of mechanical impedance mismatch through which the wave must travel. The resulting ringup in this region degrades the wave and lends a finite rise time to an initial step stress wave. Second, the periodicity of the grid creates a corrugated wave effect due to the differing material impedances. The errors resulting from this can be made small by making the thickness of the solenoid winding small.

A technique capable of eliminating the problems associated with propagating a wave through the solenoid grid

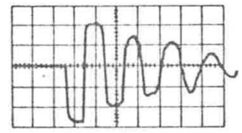

FIG. 4. Oscilloscope record of shock induced demagnetization in YIG. Periodicity corresponds to reverberation of stress wave in YIG platelet. Time scale is 0.2 μsec/div.

was developed during the course of this work. The method requires use of aluminum oxide as the material on the impact surface (see Fig. 3). The stress wave then propagates through aluminum oxide, the copper–epoxy grid, and Lucite, respectively. The material characteristics which make this technique successful are the mechanical impedance similarities of aluminum oxide and copper on one hand and Lucite and epoxy on the other, along with the similar shock velocities of copper and epoxy. This combination of properties creates a single, somewhat irregular, interface. An experiment was performed in which quartz gauges analyzed waveforms propagated through identical geometries with the exception that one contained a copper–epoxy grid while the other did not. The waveforms were experimentally identical, verifying this technique.

IV. DEMAGNETIZATION ANALYSIS

Shock induced demagnetization of the magnetic specimen is determined from the emf developed across the pickup coil. A high impedance pickup circuit is used to minimize current flow in the pickup coil. A typical oscilloscope record from which magnetic information is deduced is shown in Fig. 4. A negative emf is developed during the first transit of the shock wave resulting from the expected demagnetization of the material. The subsequent oscillation is produced by alternate remagnetization and demagnetization as the stress wave reverberates back and forth in the slab of magnetic material.

To relate demagnetization to the developed emf, it is assumed that a steady state shock profile S is progressing through the magnetic material as shown in Fig. 5. In the spirit of mechanical shock wave jump condition calculations,[10] consider, prior to passage of the shock wave, an element of area $bD\delta t$ which is compressed to $b(D-u)\delta t$ after passage of the shock wave. b is the width of the pickup coil, D is the shock velocity, and u is the particle velocity behind the shock. The change in magnetic flux across the shock wave is

$$\delta\Phi = b[B(D-u) - B_0 D]\delta t,$$

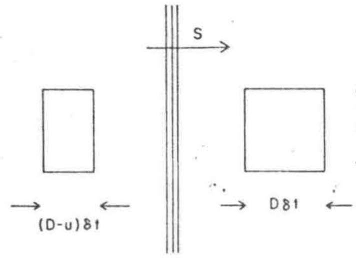

FIG. 5. Geometry for magnetic flux jump condition. Area compression due to shock propagating through magnetic medium at rest is represented. Magnetic field is normal to the page.

where B_0 is the initial magnetic induction in front of the shock and B is the final magnetic induction behind the shock. If the external applied field is constant and the demagnetizing field is zero, using

$$B=H_e+4\pi M \tag{4}$$

along with the conservation of mass jump condition

$$(D-u)\rho=D\rho_0 \tag{5}$$

yields

$$\delta\Phi=bD[4\pi(M\rho_0/\rho-M_0)+(\rho_0/\rho-1)H_e]\delta t. \tag{6}$$

M_0 is the initial magnetization per unit initial volume and M is the final magnetization per unit final volume. Since

$$u=D(1-\rho_0/\rho) \tag{7}$$

from Eq. (5) and $M\rho_0/\rho$ is the final magnetization per unit initial volume, the rate of flux change becomes

$$d\Phi/dt=4\pi bD\Delta M-buH_e. \tag{8}$$

The first term is the flux change due to the reduction in magnetization. The second term is the flux change due to the motion of the front surface of the pickup coil in the manner of a magnetic velocity gauge. In the present work the second term was quite small compared to the first. With Eq. (8), the demagnetization can be related to the recorded emf through Faraday's law.

The only significant complication encountered in using this analysis to reduce the demagnetization data was created by lateral relief waves in the platelets of YIG. The stretching of the relieved material increased the induced anisotropy effect in this region. A correction of this relief wave problem was necessary.

V. DISCUSSION

The present work for which the experimental technique was designed did not test the limits of its capabilities. The maximum fields obtained were about 1 kG. This requires a maximum current of about 35–40 A with an initial capacitor voltage of 750 V. The system is capable of carrying 150 A maximum current with only 10° to 15° temperature rise in the solenoid windings. This is substantially below the softening point of epoxy (~80°C). The technique is easily capable of producing pulsed fields up to 5 kG. The magnetic forces involved are still small compared to the strength of the materials used.

Switching the high voltage becomes a problem. For this work, a maximum voltage of 750 V was easily switched with a single silicon controlled rectifier (SCR). SCR's with blocking voltage capabilities higher than 1000 V become increasingly expensive. However, series operations of SCR's allow switching of voltages up to 3 or 4 kV.[11] For higher voltage, a spark gap technique should be used.

Since most impact studies are carried out in evacuated chambers, electrical breakdown and discharge is a potential difficulty. Care must be used in selection of cables and tank connectors for carrying the high voltages. All electrical circuitry within the chamber should be potted in insulating epoxy.

In the present work, maximum shock pressures in the solenoid and specimen were on the order of 45 kilobars. The survival time of the solenoid was about 15 to 20 μsec while that of the pickup coil was about 2 μsec. This was substantially more time than was required to perform the measurement. Survival would become a problem with increasing stress.

Although this technique was invented for investigation of shock induced anisotropy in yttrium iron garnet, it is potentially capable and sensitive enough for impact study of other magnetic and magnetostructural properties. The following possible application is suggested. Volume dependence of magnetic properties such as ferromagnetic or ferrimagnetic exchange integrals has usually been studied by hydrostatic techniques. This becomes increasingly cumbersome with increasing pressure. Shock wave techniques represent a highly sensitive means for investigating pressure dependent magnetic properties. This is because of the extremely high strain rates obtained and, therefore, extremely high flux rates expected. Unfortunately observation of this effect in homogeneous ferromagnetic material is prohibited by the much larger shock induced anisotropy effect. A possible method for circumventing the shock induced anisotropy effect would be to introduce the magnetic material, in powder form, into a low yield matrix such as Lucite or epoxy.[12] For properly chosen powder size, nearly hydrostatic conditions would obtain in the magnetic particles within a reasonable time behind the shock front. With a steady state stress profile in the magnetic composite, the analysis in the last section would provide the change in magnetization. The sensitivity of the technique is on the order of 1 V/G. This sensitivity should be more than sufficient for measuring expected demagnetization in many magnetic materials.

ACKNOWLEDGMENTS

Thanks are extended to Dr. E. B. Royce for fruitful discussion during the course of this work and to Dr. G. E. Duvall under whose encouragement and counsel this work was performed.

* Based on a thesis submitted to the Department of Physics, Washington State University, Pullman, Wash., in partial fulfillment of the Doctor of Philosophy degree, 1971. This work was supported by the Air Force Office of Scientific Research, Grant No. AFOSR-69-1758.

† Present address, Stanford Research Institute, Menlo Park, Calif. 94025.

[1] E. B. Royce, in *Physics of High Energy Density* (Academic, New York, 1971).
[2] G. R. Fowles, G. E. Duvall, J. Asay, P. Bellamy, F. Feistmann, D. Grady, T. Michaels, and R. Mitchell, Rev. Sci. Instrum. 41, 984 (1970).
[3] D. E. Grady, J. Appl. Phys. (to be published).
[4] D. E. Grady, G. E. Duvall, and E. B. Royce, J. Appl. Phys. (to be published).
[5] The topic of pulsed magnetic fields is well discussed by H. Zijlstra, *Experimental Methods in Magnetism* (Wiley, New York, 1967), Vol. I.
[6] Semi-Elements Inc., Saxonburg, Pa.
[7] The Wilkinson Company, P. O. Box 1307, Westlake Village, Calif.
[8] L. M. Barker and R. C. Hollenbach, J. Appl. Phys. 41, 4208 (1970).
[9] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Palo Alto, Calif., 1964), Vol. II.
[10] G. E. Duvall and G. R. Fowles, in *High Pressure Physics and Chemistry*, Edited by R. S. Bradley (Academic, New York, 1963), Vol. II.
[11] *General Electric SCR Manual*, 4th ed. (General Electric, New York, 1967).
[12] This would also allow investigation of conducting magnetic materials since eddy current effects would be eliminated by the nonconducting matrix.