

## Method for Shock Wave Investigation of Magnetic Material\*

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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<sup>1</sup> 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.<sup>2</sup> 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.<sup>1,3,4</sup> 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.

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

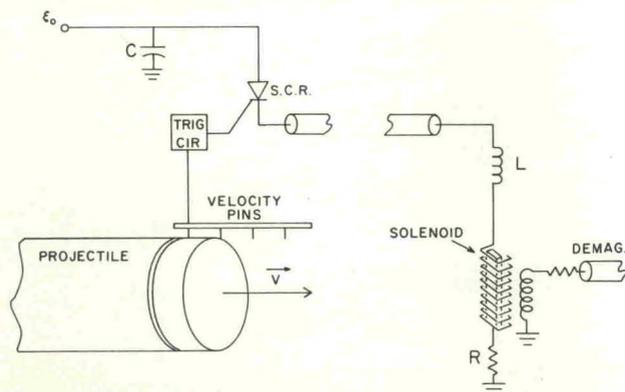


FIG. 1. Schematic representation of experimental method. Current supply is triggered by projectile contact with velocity pin. Planar impact occurs between projectile and solenoid when current (and magnetic field) in solenoid is maximum.

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<sup>5</sup>

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

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

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

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  $\Omega$  resistor paralleling the solenoid to ground. This resistor carries several percent of the total

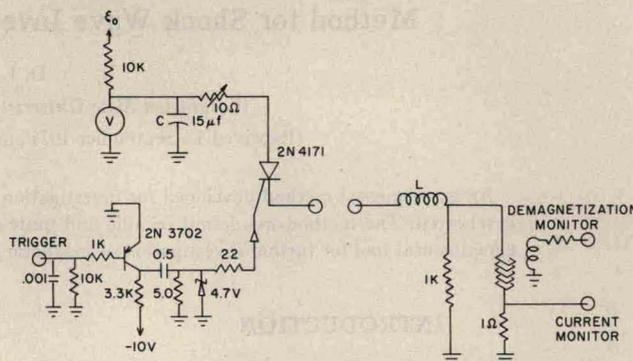


FIG. 2. Current supply and target circuit.

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  $\Omega$  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.<sup>6</sup> The dimensions were 0.1  $\times$  1.0  $\times$  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  $\times$  0.38 mm  $\text{OFHC}$  copper ribbon.<sup>7</sup> Usually between 12 and 20 turns per centimeter were used. The solenoid constitutes about 6–9  $\Omega$  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.

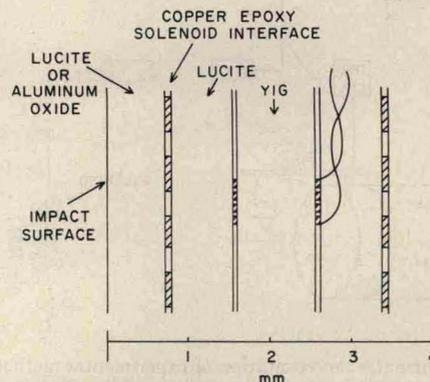


FIG. 3. Cutaway cross section of solenoid. Exhibits approximate dimensions and construction of solenoid.