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Experimental measurements of shock induced changes to the magnetization of unexploded ordnance

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ABSTRACT

Millions of acres of land around the world are potentially contaminated by unexploded ordnance (UXO). Magnetometry is a technique widely used to both detect and characterize buried UXO. It has been hypothesized that ordnance suffer a large shock on firing and impact that erases any preexisting remanent magnetization. If such demagnetization occurs, an apparent remanence metric has been shown to be effective at distinguishing hazardous ordnance from non-hazardous metallic debris. To test the shock demagnetization hypothesis, an experiment was conducted at a firing range to measure the magnetic remanence of sixty-five inert 81 mm mortars before firing and after impact. As delivered, 64 of the 65 rounds had very low remanent magnetization and a magnetizer had to be used to impose various amounts of remanence on the mortars. Three different categories of initial remanent magnetization were created (low, medium and high remanence) and these were fired at three different initial velocities. The mortars that initially had low remanent magnetization acquired a magnetization in the direction of the Earth's inducing field after impact, with the amount of re-magnetization decreasing with an increasing impact velocity. This effect is known as *shock magnetization*. The mortars with medium and high initial magnetization all lost some of their magnetic remanence, with the amount of demagnetization increasing with an increasing impact velocity. However, even at the highest impact velocity, shock demagnetization of initially highly magnetized mortars was insufficient to guarantee effective discrimination using apparent remanence.

1. Introduction

Millions of acres of land around the world are potentially contaminated by unexploded ordnance (UXO). The most well-established techniques for UXO detection are magnetics and electromagnetic induction (EMI) (Butler (2001), Nelson and McDonald (2001), Zhang et al. (2003)). These methods are very effective at not only locating UXO but also detecting many non-hazardous items such as shrapnel and cultural debris. Therefore discriminating between intact UXO and non-hazardous objects has the potential to significantly reduce clearance costs. The richer information content and the relative immunity to magnetic soil effects of EMI methods make them superior to passive magnetometers for the discrimination of detected targets (Pasion et al., 2008). However, magnetometer-based methods are still widely used, particularly in areas of difficult terrain/vegetation and for underwater applications (Salem et al., 2005). Thus, the intrinsic discrimination capability of magnetic data is still of considerable interest.

Buried munitions composed of ferrous components (e.g. steel) cause a distortion in the Earth's magnetic field that can be measured by a magnetometer. However, magnetic anomalies also arise from shrapnel and other ferrous debris, as well as from geological variations in magnetic minerals in the soils and rocks. To distinguish between a buried UXO and benign clutter or geology, an identifying feature of the magnetic anomaly of a UXO item must be determined. Ideally, we would like to be able to recover the shape and size of each detected anomaly's source and use that information for discrimination. However, there is a fundamental ambiguity in magnetic data whereby any magnetic anomaly can be represented by an equivalent layer of susceptibility (Stratton, 1941). This precludes unique recovery of a buried object's physical properties.

To proceed, we note that the response of a compact body can be decomposed into a series of moments by a multi-pole expansion (Stratton, 1941). In most cases, measurements are made in the far-field of the object (i.e. at distances several times the object's dimensions) so that the response of the dipole component dominates the measured anomaly. Higher order moments decay rapidly with distance and we can therefore usually only recover a buried object's dipole moment from the observed magnetic data (Billings, 2004).

In simplistic terms, an object's dipole moment is a consequence of both remanent and induced magnetization. Remanent magnetization is present even in the absence of an inducing field and is due to ferromagnetic domains in the steel being locked into alignment sometime during the object's history. Induced magnetism arises because magnetic domains in a ferrous material tend to align with the direction of the ambient field (Stratton, 1941).

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Artillery projectiles and mortars will suffer at least two large shocks: one during the initial firing of the projectile or mortar and the other on impact with the ground. Altshuler (1996) postulated that the shocks experienced during firing and impact partially erase the remanent magnetization of a UXO item. He further noted that the direction of induced magnetization in typical munition items is constrained to lie within about 60° of the Earth's field. Billings (2004) developed the apparent remanent magnetic discrimination method to exploit these shock induced changes to magnetization. Magnetic data from each anomaly are inverted to produce an initial dipole model. This recovered dipole model m is then compared to a family of induced magnetic responses of all munition items suspected at the site. An apparent remanence γ is computed as

$$\gamma = \frac{100\|\Delta m\|}{\|m\|} \tag{1}$$

where Δm is the minimum deviation of the recovered dipole moment from the induced dipole for an ordnance item. The deviation is normalized by the magnitude of the estimated dipole ($\|m\|$) to produce a percentage. This comparison process defines an apparent remanent magnetization for each target in the ordnance library and allows a discrimination ranking criteria to be established. Due to shock demagnetization, UXO items in the munition library that are encountered at a site are hypothesized to have low values of apparent remanence. Geological anomalies, shrapnel and other metallic debris will, in general, not match the induced model very well and hence will have large values of apparent remanence. The premise of correlating the likelihood of targets being UXO with low apparent remanence was tested at several Montana sites and was shown to be a reliable process for classification (Billings, 2004; Billings and Youmans, 2007). However, later measurements collected at two live sites by Billings (2009) raised some doubts about the general applicability of apparent remanence for ordnance discrimination. The present work therefore seeks to develop a more comprehensive understanding of the physical phenomena behind the apparent remanence method.

We describe an experiment conducted at the Aberdeen Test Center (ATC) in 2009 where the remanent magnetization of sixty-five inert 81 mm mortars were measured both before and after-firing in a series of controlled tests. The mortars were filled with a wax simulant to ensure that their mass was the same as live rounds. The ATC firing tests were intended to determine:

- Whether shock demagnetization reduces the amount of remanent magnetization remaining after impact;
- Whether ordnance are re-magnetized in the Earth's field after shock demagnetization;
- How impact velocity affects the amount of shock demagnetization that occurs; and
- Whether rounds with extremely large remanent magnetization undergo sufficient shock demagnetization to be correctly classified using the apparent remanence method.

Shock and stress induced changes to magnetization of metals and rocks have been the focus of a large volume of literature in a number of fields including paleomagnetization (e.g. Louzada et al., 2010) and non-destructive testing (e.g. Staples et al., 2013). In 1949, Brown investigated changes to magnetization caused by mechanical disturbances and related them to the hysteresis loop (Brown, 1949). Brown changed the independent variable in Rayleigh's Law from magnetizing force to stress. He postulated that the magnetizing force or stress causes displacements of the walls separating adjacent domains and more favorably magnetized domains grow at the expense of their neighbors. Nagata (1971) showed that isothermal remanence carried by a rock can be substantially reduced, and a remanence proportional to the ambient field can be acquired at pressures comparable to those suffered by a rock when struck by a geologic hammer. Gattacceca et al. (2010) conducted experiments to better understand shock demagnetization and shock remanent magnetization (SRM) caused by high velocity impacts of planetary or asteroidal surfaces. They found that the amount of SRM was independent of the initial remanence and dependent only on the strength and direction of the field at the time of impact.

2. Materials and methods

Billings (2009) describes the "Magnetic Remanence Interrogation Platform" (MRIP), a device for measuring the contributions of the induced and remanent magnetizations of a steel item. The MRIP comprises six three-component fluxgate magnetometers symmetrically distributed around a rotating sample holder. Samples are placed on the holder and are slowly spun through two complete rotations. The measurement is repeated after the sample is physically rotated by 90°, so that the initial vertical axis becomes horizontal.

2.1. Selection of test-rounds

Personnel at Aberdeen Test Center conducted a study to identify projectiles that could be used for pre and post-fire/impact measurements of induced and remanent magnetic fields. A moderate size projectile was sought that had, or could easily be converted to, an inert counterpart. The size and configuration of the projectile had to be such that magnetic field readings could easily be taken with the MRIP. Another consideration was that the rounds have trajectories and impact velocities that would enhance recoverability and minimize test setup costs. By analyzing assembly, geometry, mass, trajectory characteristics and expected penetration depths an acceptable candidate was identified. The M889A1 mortar cartridge is a common round with an inert target practice counterpart: the M879 cartridge. The empty mass of the M879 is 3.3 kilograms (kg) and when wax-filled weighs the same as a M889A1 HE round (4.14 kg). Both mortar types have a diameter of 81 mm. The abundant use of the M879 round makes it easily attainable for testing. Further, mortar firing systems are easily set up, their rounds typically have small dispersions, and associated penetration depths are small. The M879 round would therefore facilitate a low test cost with good recoverability potential.

Charge increments and firing elevations were selected for the M879 to provide a variety of launch and impact shocks. Expected remanence and projectile flight characteristics are shown in Tables 1 and 2.

2.2. Test matrix

An axi-symmetric ordnance item has a much larger induced magnetization in the axial direction, m_a, than in the transverse direction m_t. From prior measurements of similar sized rounds we expected $m_t = 0.07$ amperes-meter^2 (Am^2) and $m_a = 0.24$ Am^2 for the 81 mm mortar (Billings et al., 2006). After measuring the rounds with the MRIP we were able to more precisely define these numbers as the mean values of sixty-one different MRIP measurements: $m_t = 0.0826$ Am^2 and $m_a = 0.375$ Am^2 with standard deviations of 0.0015 and 0.0041 Am^2 respectively.

The magnetic remanence discrimination method of Billings (2004) considers a round to be a UXO if the apparent remanence is <50%, although typically a larger cutoff is used to account for uncertainty in

Table 1
Mortar test-matrix showing parameters that were varied. The numbers in brackets are the actual numbers achieved in each category.

Remanence	Low	Medium		High		Total
Projectile		Trans.	Axial	Trans.	Axial	
81 mm (minimum charge)	4 (5)	4 (6)	4 (4)	4 (0)	4 (6)	20 (21)
81 mm (medium-charge)	4 (9)	4 (5)	4 (4)	4 (0)	4 (5)	20 (23)
81 mm (maximum charge)	4 (5)	4 (8)	4 (4)	4 (0)	4 (3)	20 (20)