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TRANSVERSE EXPLOSIVE SHOCK-WAVE COMPRESSION OF $Nd_2Fe_{14}B$ HIGH-ENERGY HARD FERROMAGNETS: INDUCED MAGNETIC PHASE TRANSITION

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Abstract. Investigations of the magnetic phase state of $Nd_2Fe_{14}B$ high-energy hard ferromagnets under the action of an explosive shock wave traveling across the magnetization vector, **M**, have been performed. We demonstrate that the transverse shock-wave compression of an $Nd_2Fe_{14}B$ hard ferromagnet with pressure at the shock wave front of P = 22.3 GPa causes a hard ferromagnet – to – weak magnet phase transition. Due to this phase transition, the magnetostatic energy stored for an indefinite period of time in the $Nd_2Fe_{14}B$ ferromagnet is released within a short time interval and can be transformed into pulsed primary power. Based on this effect we have developed a new type of ultracompact (volumes from 9 to 50 cm^3) autonomous explosive-driven source of primary power that is capable of powering a magnetic flux compression generator with current up to 4 kA, and of charging high-voltage Arkadiev-Marx type generator capacitor banks.

Keywords: shock compression of solids, magnetic phase transition, hard ferromagnet, explosive pulsed power
PACS: 84.90.+a, 84.60.-h, 62.50.+p, 47.40.-x, 89.30.-g, 75.50.Vv, 75.90.+w.

INTRODUCTION

The generation of primary power by autonomous pulsed sources is critical to the success of many scientific projects and engineering applications. Explosive-driven electric generators can be considered to be the most efficient compact pulsed power devices. The first attempt at pulsed power generation by explosive-driven electrical transducers based on shock wave demagnetization of soft ferromagnetic materials was made in the late 1950s [1]. A schematic diagram of the pulsed generator based on demagnetization of a closed soft ferromagnetic core by shock waves generated from an accelerated pellet is shown in Fig. 1 [1].

The ultimate output current produced by this type of explosive-driven generator with 150–200 cm^3 closed soft ferromagnetic cores was in the range of $I(t)_{max}$ = 700–800 A with full width at half maximum (FWHM) of about 1 μs [1]. The high conductivity of closed soft ferromagnetic core material when shock compressed was previously considered to be the main reason for the low output parameters of these generators [1]. However, there

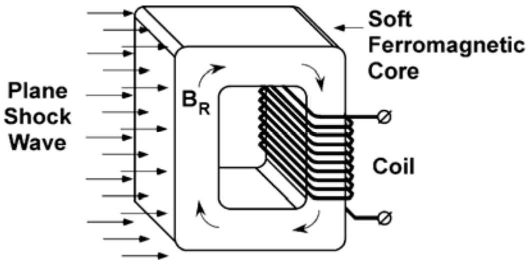

Figure 1. Schematic diagram of an explosive-driven electrical transducer based on the shock wave demagnetization of a closed soft ferromagnetic core.

are two more important circumstances that determine the restrictions imposed on the generators of this type that have never been mentioned before, but are the key physical principles of primary pulsed power generation by ferromagnetic shock wave generators:

1. The generators [1] (Fig. 1) are not autonomous sources of primary power. The closed soft ferromagnetic core must be magnetized to saturation immediately before explosive operation. Therefore, an exciting electric current $I_{exc}(t)$, generated by electrochemical batteries, was passed through the generating coil in [1] (Fig. 1). Thus, pulsed systems of this type should be considered as systems being comprised of closed soft ferromagnetic cores and sources of exciting electric current (the latter are the actual autonomous sources of primary power in these systems).

2. The electromagnetic energy density that can be stored by soft ferromagnets is extremely low. Indeed, the magnetostatic energy E stored in a magnetized body can be expressed as a volume integral of the scalar product **(B·H)** taken at each point in the magnetic medium:

$$E = -0.5\iiint_V (\mathbf{B}\cdot\mathbf{H})\cdot dv\,. \qquad (1)$$

For soft ferromagnets used in closed ferromagnetic cores (Fig. 1), the maximum energy product, $(\mathbf{B}\cdot\mathbf{H})_{max}$, is 6–7 orders of magnitude less than the corresponding value $(\mathbf{B}\cdot\mathbf{H})_{max}$ for hard high-energy ferromagnets. Therefore, E stored in soft ferromagnets [Eq. (1)] is also 6–7 orders of magnitude lower than the energy stored in hard ferromagnets.

The total energy delivered by a generator in a load circuit, $W(\infty)$, can be written as follows:

$$W(\infty) = \int_0^{+\infty} I(t)\cdot U(t)\cdot dt\,, \qquad (2)$$

where $I(t)$ is the electric current in the load circuit and $U(t)$ is the electric potential across the load. Since the total energy, $W(\infty)$, delivered by the generator in the load circuit cannot exceed the energy, E, initially stored in the system [see Eq. (1)], it is obvious that only high-energy hard ferromagnetic materials used as energy-carrying elements in explosive-driven ferromagnetic generators can generate decent currents, $I(t)$, and voltages, $U(t)$, in actual loads. Proceeding from this, there are no grounds to believe that soft ferromagnetic cores can efficiently generate prime energy in the generators as shown in Fig. 1.

The understanding of this fundamental principle was reached several years ago [2-4]. In this regard, it seemed to be of importance to find an efficient technique for quick initiation of the hard ferromagnet – to – weak magnet phase transition in high-energy rare-earth hard magnetic materials for the purpose of releasing, within a short time, the entire amount of magnetostatic energy stored in the ferromagnet in the form of pulses of high voltage, high current, and high power.

The first experimental investigations of the phase state transitions in hard ferri- and ferromagnets, under the action of high pulsed pressure, were performed several years ago [2-4], forty years after the investigation of the magnetic phase transition in soft ferromagnetic materials. It was for the first time demonstrated that high-energy hard ferrimagnet ($BaFe_{12}O_{19}$) and ferromagnet ($Nd_2Fe_{14}B$) undergo hard ferri/ferromagnet – to – weak magnet phase transition under longitudinal-shock-compression (the shock wave propagated along the magnetization vector **M**) [2-5]. Practical application of these phase transitions made possible the development of the first actual autonomous explosive-driven shock wave ferromagnetic generators of primary power [2-4]. Somewhat later, the $Nd_2Fe_{14}B$ hard ferromagnet – to – weak magnet phase transformation, caused by the transverse shock-wave compression (the shock wave traveled across the magnetization vector **M**) [6,7], was detected. In the present study, the state of the art of investigations of the $Nd_2Fe_{14}B$ high-energy hard ferromagnet – to – weak magnet phase transition under transverse shock wave compression is presented and practical applications of this phase transition for generation of primary pulsed power are briefly described.

THE EFFECT OF TRANSVERSE SHOCK-WAVE DEMAGNETIZATION OF $Nd_2Fe_{14}B$

A schematic diagram of one of the most successful designs [6-8] for experimental study of the effect of transverse shock wave compression on the phase state of solids is shown in Fig. 2. In our design, the hard ferromagnetic energy-carrying element is an $Nd_2Fe_{14}B$ hollow cylinder magnetized along its axis [6-10]. The through-hole in the center of the cylinder is where the high explosives and detonators are inserted. As demonstrated in our experiments (Fig. 3 and Table 1), 0.8 g of desensitized RDX high explosives are sufficient for complete demagnetization of the $Nd_2Fe_{14}B$ cylinders having outer diameter *O.D.* = 25.4 mm, inner diameter *I.D.* = 7.6 mm, and length h = 19.1 mm (the cylinder mass was m = 65 g and volume 8.75 cm^3). Pulsed pressures at the shock wave front were estimated at P = 22.3 GPa [3].

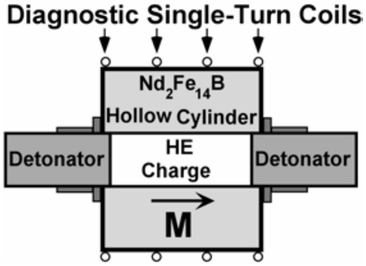

Figure 2. Schematic diagram of the generator used for investigating magnetic phase transition under transverse shock-wave compression of $Nd_2Fe_{14}B$.

Experimental waveforms of the electromotive force (EMF) pulses, $E_g(t)$, shown in Fig. 3, were recorded from four single-turn thin coils (see Fig. 2). According to Faraday's Law, the change in the magnetic flux, $\Delta\Phi(t)$, is:

$$\Delta\Phi(t) = -\int_0^t E_g(t)\,dt\,. \qquad (3)$$

TABLE 1. Calculated initial magnetic flux, Φ_0, for the indicated positions of the diagnostic coils wound on the $Nd_2Fe_{14}B$ hollow cylinder and experimentally measured losses of magnetic flux, $\Delta\Phi_f$, of the high-energy $Nd_2Fe_{14}B$ ferromagnets under transverse shock wave compression.

Coil #	#1	#2	#3	#4
z (mm)	–9.5	–3.2	+3.2	+9.5
Φ_0 (μWb)	251	371	371	251
$\Delta\Phi_f$ (μWb)	–231 ± 17	–351 ± 21	–351 ± 21	–231 ± 17

The initial magnetic flux, Φ_0, linking the single-turn diagnostic coil can be numerically calculated [2-8,10]. A comparison of the initial magnetic flux, Φ_0, and the magnetic flux change recorded in our explosive experiment (Table 1) demonstrates that the transverse shock wave accounts for more than 90–92% demagnetization.

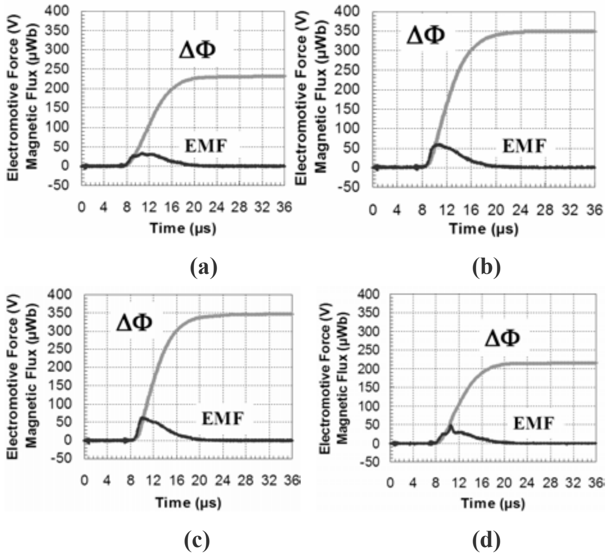

Figure 3. Experimental waveforms of EMF pulses $E_g(t)$ (black curves) and magnetic flux changes $\Delta\Phi(t)$ [gray curves, Eq. (3)] detected by four single-turn diagnostic coils located on the hollow $Nd_2Fe_{14}B$ high-energy hard ferromagnetic cylinder compressed by a transverse shock wave. The function ΔΦ(t) is shown with the opposite sign. The diagnostic coils numbered from left to right (see Fig. 2) are at distances z = –9.5 mm (coil # 1) (a), –3.2 mm (coil # 2) (b), +3.2 mm (coil # 3) (c), and +9.5 mm (coil # 4) (d) from the center of the cylinder.

APPLICATIONS OF TRANSVERSE SHOCK-WAVE DEMAGNETIZATION OF $Nd_2Fe_{14}B$

Based on the effect of transverse shock-wave demagnetization of $Nd_2Fe_{14}B$ hard ferromagnets we designed, built, and tested a series of ultracompact explosive-driven high-voltage prime power generators [6]. A high-voltage pulse produced by a transverse shock wave ferromagnetic generator (FMG) containing an $Nd_2Fe_{14}B$ energy-carrying element of 8.75 cm^3 volume and 361-turn pulse-generating coil is shown in Fig. 4. The amplitude of the pulse was $U(t)_{max}$ = 14.7 kV with FWHM of 9.18 μs. We performed studies of the generation of high-voltage pulses by FMGs containing generating coils up to 750 turns. The results demonstrated that output high-voltage pulse amplitude is directly proportional to the number of turns.

The primary energy, $W(t)$, produced by the high-voltage transverse FMG can be used for charging an Arkadiev-Marx generator. The energy transferred from the FMG (volume 8.75 cm^3) to a 18 nF capacitor bank was $W(\infty)$ = 0.38 J. The peak power in the load circuit reached $P(t)_{max}$ = 43 kW. The maximum charge transferred to the capacitor bank was $Q(t)_{max}$ = 111 μC.

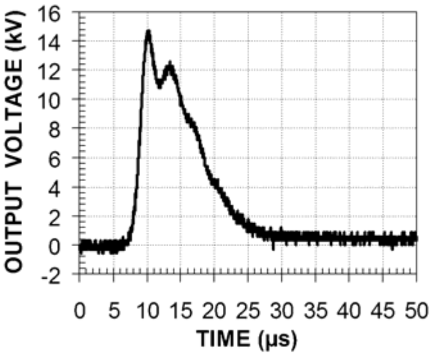

Figure 4. A typical waveform of output pulse produced by high-voltage FMG (see the text).

Several designs of high-current FMGs were developed and detailed investigations of the generation of high-current pulses by ultracompact FMGs of volumes 8.6 to 50 cm^3 was performed [6-10]. One of the possible applications of high-current FMGs is powering the magnetic flux compression generators (MFCGs), the most effective explosive-driven pulsed power amplifier. FMG seed sources are significantly smaller, lighter and more reliable in operation than traditional MFCG seeding systems based on electrochemical cells and electronic circuits. The FMG containing $Nd_2Fe_{14}B$ energy-carrying element of volume 50 cm^3 is capable of producing in the seed coil of an MFCG the high current pulse of amplitude $I(t)_{max}$ = 4180 A with FWHM of 52.7 μs [8,10]. In direct experiments we demonstrated successful operation of a completely explosive pulsed power mini-system containing an FMG as a prime power source and the MFCG as a pulsed power amplifier [9].

SUMMARY

In this work we have demonstrated:

1. The fundamental limits of explosive-driven electrical transducers based on shock demagnetization of soft ferromagnets.

2. The physical principles of the effect of transverse explosive shock-wave demagnetization of the $Nd_2Fe_{14}B$ high-energy hard ferromagnet.

3. Practical applications of the effect of transverse explosive shock-wave demagnetization of $Nd_2Fe_{14}B$ high-energy hard ferromagnets for generating primary pulsed power.

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