

PULSED MAGNETIC METAL FORMING

by

FRED JAMES WILLIAMS

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

BACHELOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

(February 1979)

Signature of Author
Department of Mechanical Engineering
January 19, 1979

Certified by
Thesis Supervisor

Accepted by
Archives Chairman, Departmental Committee on Thesis

MASSACHUSETTS INSTITUTE
OF TECHNOLOGY

APR 5 1979

LIBRARIES

PULSED MAGNETIC METAL FORMING

by

FRED JAMES WILLIAMS

Submitted to the Department of Mechanical Engineering on January 19, 1979 in partial fulfillment of the requirements for the Degree of Bachelor of Science.

ABSTRACT

The objective of this paper is to communicate the experience, conclusions and insights gained during the design and construction of a pulsed magnetic metal forming system built at the Francis Bitter National Magnet Laboratory for use in ongoing experiments in magnetic metallurgy. The forming system will be used in future experiments on welding and mechanical bonding of similar and dissimilar metals and also on magnetic swaging of superconducting wire terminations to increase conductivity.

The system that was constructed consists of a 9 K joule bank of high voltage (20Kv) capacitors, an ignitron switch, charging and firing circuits, and a single turn pulse coil. The system created magnetic field pulses with a peak field of 330 K gauss and a half period of 6 μ seconds. This type of fast rising pulse induces opposing currents in the work piece which apply forces that tend to compress the conductor. These forces reach a level equivalent to a pressure of 65,000 psi applied to the outside of the cylinders. The system was successful in swaging thin wall samples of copper,

steel, and aluminum. Results indicate that its performance will be adequate for the initial phases of the project for which it was built. Calculations and measurements of the coil performance are presented.

Thesis Supervisor: D. Bruce Montgomery

Title: Associate Director,
Francis Bitter National Magnet Laboratory

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	2
I. INTRODUCTION	5
II. THEORY	7
III. EXPERIMENTAL WORK	14
IV. ANALYSIS	19
V. HISTORY	38
VI. CONCLUSIONS	41
REFERENCES	45
BIBLIOGRAPHY	46

I. INTRODUCTION

Magnetic metal forming is a process by which electrical energy is used directly through magnetic field interactions to apply forces to a conductive metal. These forces are usually applied between the pulsed field of an air core solenoid and the currents that this field induces in the workpiece. Therefore, no physical contact is necessary and the workpiece can be easily isolated in a vacuum or inert atmosphere when this is desirable.

The project that I have been involved in for the past six months required the development of a pulsed magnetic metal forming system that could be used for a variety of planned experiments in magnetic forming and welding. What was required was a system that could compress two concentric thin walled metal tubes, of about one-half inch in diameter, with a force sufficient to exceed their yield strength and cause the two surfaces to flow plastically into intimate contact with each other. The system that I build to accomplish this consisted of a high voltage capacitor bank connected to a single turn coil.

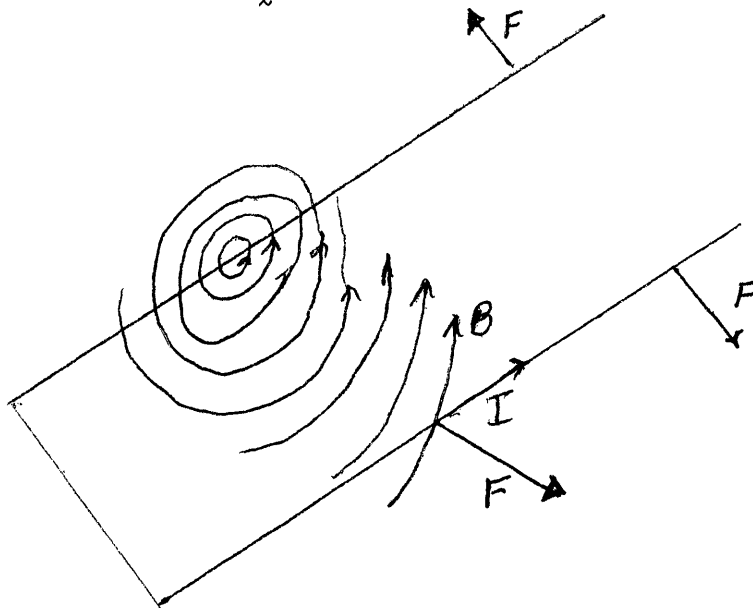
There are a number of considerations that make construction of a system such as this fairly complicated. Because these complications are not always obvious in the formal mathematical expressions of electrodynamics, it is necessary to develop a clear intuitive understanding of what is happening in the high power capacitor discharge system and in the magnetic field within the coil.

In addition, it is helpful to develop a feel for the magnitude of the parameters associated with commonly available components. Toward this end I have found it most helpful to keep all analysis simple and basic. By relying on first order approximations it is easier to keep the relationships of the basic parameters clear and although the results may only be accurate within 20%, it is easier to focus attention on those parameters which may be able to affect the results by an order of magnitude or more.

II. THEORY

The simplest and most basic magnetic effect is that between two parallel current carrying wires. This effect can be observed directly in the physical motion of the wires if they carry an appreciable current (>10,000 amps). When the current flows through the wires it creates a magnetic field between the wires. The current interacts with this field and the two conductors push or pull against one another. This is the basic Lorentz force relationship and

follows the equation $\frac{F}{\ell} = i \times B$



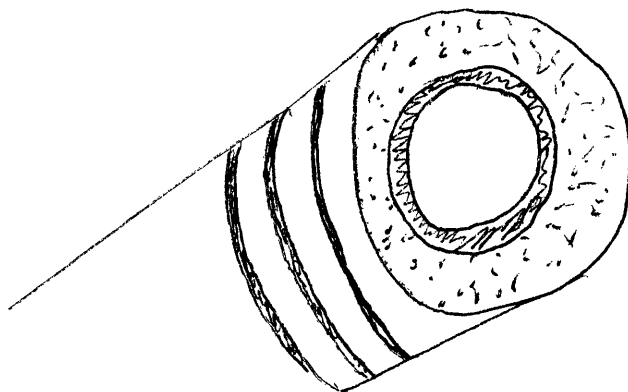
where $\frac{F}{\ell}$ = Force/unit length ($\frac{\text{Newtons}}{\text{meter}}$)

i = current (amps)

B = magnetic field (tesla = 10^4 gauss)

The next effect to observe is that between a single wire carrying a current pulse and the surface of a conducting sheet. If the pulse is short ($<1\text{ms}$) then the current will produce a changing magnetic field which will induce an image current or eddy current in the conducting sheet. The wire will then behave as though it were one of two parallel wires carrying opposite current and the wire will be repelled from the sheet. The induced current is always opposite in direction to the current that causes it and therefore induced currents usually repel. Since the force is applied to the induced currents the force will only appear while the field is changing. A steady current will not apply force to a nearby conducting sheet.

Another simple geometry consists of a number of turns of insulated wire surrounding a conducting cylinder. If a large current is applied to this coil for a short period of time then there will be a changing magnetic field within the coil. This changing magnetic field induces an opposite current in the conducting cylinder which tends to exclude the field from the inside.



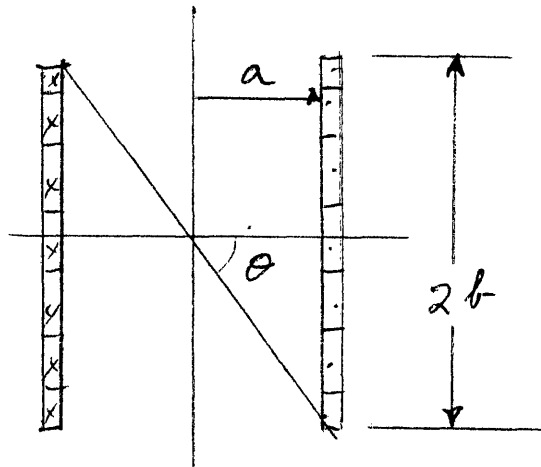
If the cylinder is close to the surrounding coil and if the pulse is fast then each turn of the coil will produce an image current in the conducting cylinder which pushes against that turn and all other turns in the coil. The net effect is a pulse of force applied to the conducting cylinder which tends to compress the cylinder and expand the coil. A way to visualize this process is to consider the B field between the cylinder and coil to be equivalent to a two-dimensional gas under pressure which exerts a pressure in the radial direction only. This gas pressure would be equivalent to about 6,000 psi for a field of 100K gauss (an iron core magnet has a maximum field of about 20K gauss) and the pressure is proportional to B^2 . This means that at a field of 300KG the pressure would be $9 \times 6,000$ or 54,000 psi. This represents about the highest field that can be maintained in a steady state by a cooled magnet because the pressure on the inside turns of the magnet is approaching the compressive strength of copper alloys.

It is possible presently to make pulsed coils of solid conductor with no provision for steady-state cooling, that have sufficient strength to produce fields of 500 Kg in a small volume. The pressure equivalent to this field would be $(5)^2 \times 6,000 = 150,000$ psi. The pressure corresponds to the internal compressive strength of the strongest berrilium copper alloy.

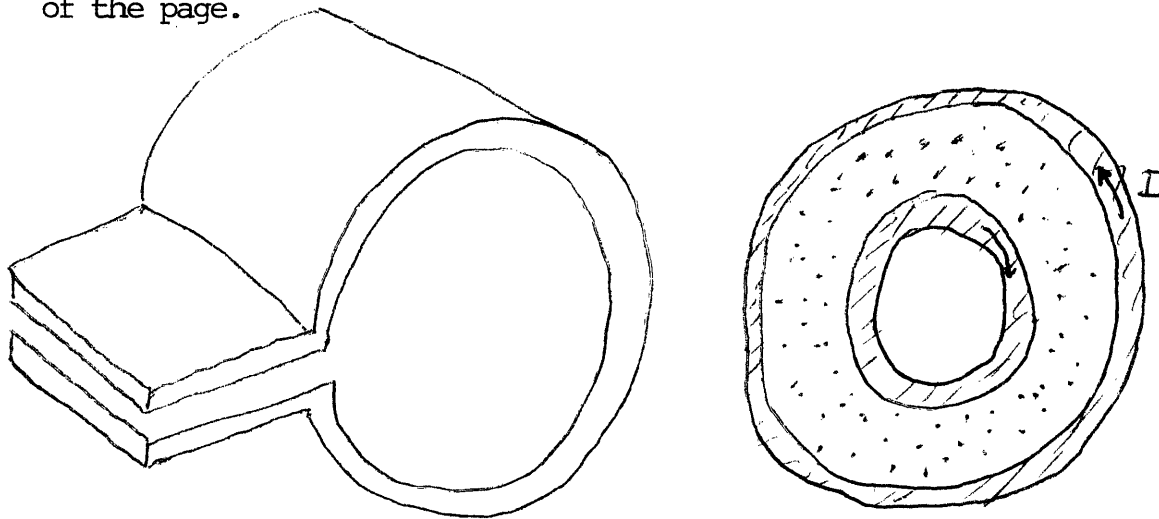
The field within a simple solenoid can be calculated as follows:¹

$$B_o = \frac{4\pi}{10} I' \frac{b}{(a^2+b^2)^{3/2}} = \frac{4\pi}{10} I' \cos\theta$$

where $I' =$ current per unit length $= \frac{NI}{2b}$ amp/cm



A cylindrical geometry is a convenient configuration in which to discuss in detail the effect of induced current interactions. Consider for example a single turn coil. Except for small variations near the slot this coil looks like a thin solid current sheet. From the end it appears as a circle with the flux lines coming out of the page.



If a conducting cylinder such as a copper tube is placed inside the coil it will tend to shield its interior from magnetic field changes. If the current in the outer coil changes rapidly (<1ms) then the field change that it is generating will not have time to penetrate through the inner cylinder but instead will set up induced eddy currents that flow in opposition to the main coil current and keep the field within the center from changing. These two currents push against each other or more accurately they both push against the B field as if it were a compressible two-dimensional gas.

As time passes the induced current begins to die out due to normal resistance and the field will begin to penetrate through the inner cylinder. The resistance of the inner cylinder depends on its thickness and the material of which it is made. If it is fairly thick and the pulse is fast enough then it will completely shield the interior and the induced current will flow mostly at the surface. If the conductor is thin or the pulse long then the field will partially penetrate and the induced current will flow through the entire cross section. If the conductor is just exactly thick enough to exclude two-thirds of the flux for a given pulse length then the current will have a distribution with most of the current near the surface. This thickness which just barely excludes the field is known as the skin depth for that particular pulse length and material. A simple formula which gives this relationship is

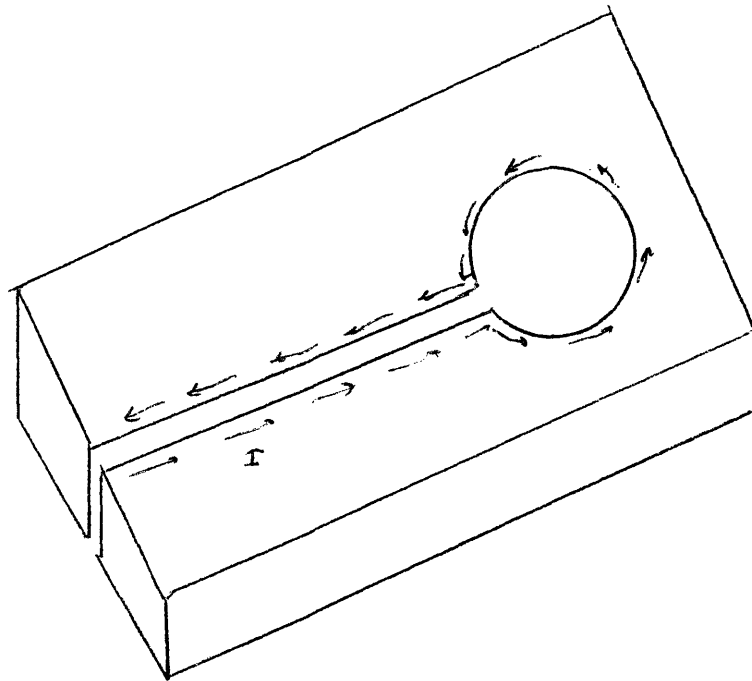
$$S = .296\sqrt{K T}$$

where $K = \frac{\rho}{\rho_0}$ = ratio of resistance to that of copper

T = half period of pulse in milliseconds

S = skin depth in cm.

The same skin depth effect is observed in the pulse coil itself. If the pulse is short enough then the current will tend to flow entirely on the inside lip of the coil and the rest of the conductor will not have any appreciable current flow and therefore no direct I^2R heating. This effect makes it possible to construct a coil from a solid conductor in which the bulk of the material is used only for mechanical support yet does not have to be insulated from the current carrying portion of the coil.



This same concept can be used to create a very strong helical winding by making a helical slot in a thick tube. Coils of this construction are very strong, however, they are considerably more complicated to construct than a single turn coil. Since the helical coil has many turns it will have more inductance and therefore will make for a longer pulse time or a higher operating voltage. Since the inductance of the leads is constant, a multi-turn coil will be more efficient in transferring capacitor energy from the capacitor to the magnetic field and less energy will be trapped in the inductance of the leads and switches.

There is another coil configuration which deserves attention. This is a coil constructed by winding up a flat tape to produce a spiral winding. Since the turns are insulated from one another the current is forced to flow throughout the winding and the heating is not all concentrated at the inside lip. However, this design sacrifices much of the strength found in solid or helical coils because the hoop stress must be transmitted across the insulation between turns.

III. EXPERIMENTAL WORK

After reviewing some of the literature, and discussing some past experimental work with Henry Kolm, and working through some initial design ideas, I started checking around the Magnet Lab to see what equipment might be available for use. I found that there were several old ignitron capacitor discharge units (manufactured by EG&G) that were not being used and I decided that they would make a good starting point for the experimental work.

I cleaned up one of these units and checked out the firing circuitry and built a suitable trigger source. Next I started looking at the coil design problem. I had spend a lot of time thinking about coil designs in the past and felt that a single turn coil would certainly be the simplest to build and might even turn out to be the best overall design. Therefore, I made a simple single-turn coil by starting with a one-half inch thick copper plate and drilling a half-inch diameter hole near the center. Next I used a band saw to cut a narrow slot that intersected the center of the hole. This created a simple coil of low inductance and reasonable strength. I drilled two small holes near the end of the slot and used a simple piece of coaxial cable to hook the coil to the first capacitor unit which contained 3K joules of energy when fully charged 50 20KV. I used a single piece of .003 inch mylar sheet folded in half and inserted in the coil so that it went down the slot around the hole and back up to the slot again.

The insulator extended beyond the copper sufficiently to provide 20KV insulation for the workpiece, the slot, and the parallel terminations. At this point I was able to check out the capacitor and ignitron and coil up to 20KV. Using a small piece of plumbing tube as a sample, I found that the effect with only 3K joules was negligible. I concluded that I would definitely need more energy to get any significant effect.

I went down in the basement storage area and found an old bank of 5KV laser discharge capacitors that I had once used for liquid metal magnetic injection molding experiments. This bank contained 6 capacitors of 120 μ farads each. I found that one of the capacitor terminals had been broken during storage causing it to leak oil badly. Therefore, with five capacitors this bank would hold 7.5K joules when charged to 5KV. I cleaned up the rest of the capacitor terminals and hooked them in parallel with simple flat braided battery ground strap. I then took the charging and firing circuitry and ignitron switch from the first bank and adapted them to this new system.

At this point I made some improvements to the ignitron and coil terminations. I attached the 12 output coaxial cables from the ignitron to a set of flat parallel buss plates separated by a thin sheet of plastic. Next I used the milling machine to make two triangular leads for the coil to conduct the current from the long parallel plates down to the narrow coil. The adapter leads were

machined to fit over the parallel buss plates and were silver soldered into a slot machined in the coil. The coil was then clamped to the buss plates with a pair of insulated c-clamps. With this new system I measured a half-period for the ringing discharge of 85μ seconds. This corresponds to a calculated peak current of 35K amp. This system created a sufficient field to cause a thin walled copper tube to show a slight reduction in diameter by .010 inch. This was still not nearly enough effect to be useful as a magnetic forming tool. This arrangement contained much more energy, however, the pulse was so long that the peak field never exceeded the strength by much. Therefore, even though the pressure was applied for a longer time the effect was still small.

At this point I calculated that the 3K joule 20KV bank would produce a higher peak field since its ringing time would be very much shorter. I therefore transferred the ignitron and circuitry back to the original bank and together with the improved coil and ignitron terminations was able to obtain slightly better performance with a half-period of 2.2μ s and a current of 428K amps. This current created a pressure much higher than the yield strength, however, the bank did not contain enough energy to maintain this high pressure long enough to cause appreciable deformation.

I then decided to make a set of very low inductance leads for the 7.5K joule bank to replace the copper braid connections. In order to accomplish this, I started with two wide flat plates

of aluminum and drilled holes to match the capacitor terminal spacing. I then machined clamps to fit over the parallel plate arrangement and hold them together against the repulsive forces set up by the current they would carry. I installed these on the capacitor bank with three layers mylar insulation separating them, and installed an ignitron switch on the end of the plate. This configuration was successful in reducing the ringing time to a half-period of 30 μ s with a corresponding current of 314K amps and a pressure of 29,000 psi. This system was successful in collapsing a thin walled sample of copper. However, I felt that the ringing time for this slow bank was still too long and hence the spin depth would be too large for work with more resistive samples such as stainless steel.

Therefore, I obtained a second capacitor discharge unit of 3K joules and 20 KV which was identical with the first 20KV unit. I combined these two sets of capacitors with a single set of charging and firing circuits to make a bank with 6K joules total energy and a half period with my coil that was measured to be 3.1 μ s. This corresponds to a peak current of 608K amps. This was calculated to produce a field of 425K gauss which would be equivalent to a pressure of 108,000 psi. With this arrangement I was able to completely crush samples of copper and considerably compress samples such as stainless steel and brass.

I tested this arrangement with several different samples and combinations of different metals. The samples of copper were compressed considerably with very little heating in the sample.

The samples of steel however were heated sufficiently to cause the surface to turn blue. I continued testing different samples with this arrangement until one day while I was looking through a storage room I came across an old 3K joule 20KV low inductance capacitor that Henry Kolm had used on experiments to develop the double pulse technique for applying traction forces to test bonded honeycomb or remove dents from aluminum airplanes. I realized that this capacitor would be compatible with the rest of my first discharge bank and I was able to use it in parallel with the present bank to increase the energy to 9K joules. With this additional capacitance and inductance in parallel with my circuit I measured a ringing time of 6 μ s. With the increased energy delivered in this time period the peak current can be calculated to be 470K amps which corresponds to a field of 330K gauss and a pressure of 65,000 psi.

IV. ANALYSIS

In order to calculate the deformation to expect from a magnetic forming system it is necessary to know the energy and voltage of the capacitor bank and the half period of the ringing discharge. Together these factors determine the coil current and therefore the B field and the pressure exerted on the workpiece. The capacitor bank energy and voltage determines the capacitance in the series L C circuit and the charge Q on the capacitor. This amount of charge flows off the capacitor as it is being discharged to zero-volts during the current rise time. The charge and the rise time determine the average current flowing out of the capacitor and through the coil. For a ringing or undamped discharge the rise time is equal to one-half of the half period or one-fourth of a complete sin wave cycle.

$$T_o = \frac{T}{2} = \frac{1}{4} \times \frac{2\pi}{\omega}$$

To - current rise time
T = half period

During the first half cycle of the discharge the current rises from zero to a maximum and returns to zero in a sinusoidal fashion. The voltage goes from a maximum to zero and then almost to full reverse voltage. During this time the charge Q is removed from the plates as the voltage goes to zero and then a charge of almost Q is placed on the capacitor in the reverse direction. Since the discharge is a sinewave, the peak current will be $\pi/2$ times the average current. The average current is found by dividing the capacitor charge by the rise time.

$$E = \frac{1}{2}Cv \therefore C = \frac{2E}{v^2}$$

$$Q = CV$$

$$I_{avg} = \frac{Q}{T_0} = \frac{Q}{T/2} = \frac{2Q}{T}$$

$$I_{peak} = \frac{\pi}{2} I_{avg} = \frac{\pi}{2} \cdot \frac{2Q}{T} = \frac{\pi Q}{T}$$

where:

E = capacitor energy - joules

C = capacitance - Farads

V = Voltage - volts

Q = Charge - Columbs

T_0^2 = Current risetime = $\frac{T}{2}$

T = Half period or pulse width

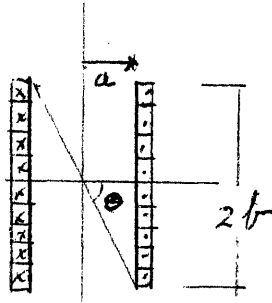
If the discharge half period is not known but the system inductance can be measured or estimated then the half period can be estimated for the L-C circuit and the current can be arrived at from the half period.

$$T = \pi \sqrt{LC}$$

where L - system inductance-henries

C = system capacitance-farads

From the peak current and coil geometry it is easy to calculate the peak B field to expect as follows :



where $I' = \frac{NI}{2b}$ amps/cm
 $\cos \theta = \frac{a}{(a^2 + b^2)^{1/2}}$

$$B_{\max} = \frac{4\pi}{10} I' \cos \theta$$

I' is the current per unit length for the coil and $\cos \theta$ is a geometry dependent factor determined by how long and slender the coil is. θ is the angle between the coil mid-plane and the diagonal across the bore of the coil.

Once the peak field has been determined, it is easy to arrive at the peak pressure exerted on the workpiece if the shilding is complete since the pressure is proportional to B^2 and a field of 100Kgauss is equivalent to a pressure of 5800 psi (≈ 6000 psi) = 4×10^7 nt/m². If the shilding is not complete, then this pressure must be multiplied by a factor of $(1-K^2)$ where K is the ratio of the field inside the workpiece to the field outside.

$$\begin{aligned}
 p &= B_{\text{outside}}^2 - B_{\text{inside}}^2 \times 58.00 \text{ pdi} \\
 &= (1-K^2) B_{\text{outside}}^2 \times 58.00 \text{ psi} \quad \text{where } p = \text{pressure} = \text{psi} \\
 &= (1-K^2) B^2 \times 4 \times 10^5 \text{ nt/m}^2 \quad \text{or nt/m}^2 \\
 &\quad \quad \quad B \text{ FIELD} = 1 \text{ tesla}
 \end{aligned}$$

The peak pressure is a function of B^2 or I^2 , and since the current is a sine wave, the pressure is a \sin^2 function and when integrated over a half cycle, the average pressure is one half of the peak pressure.

The impulse or momentum transferred to this workpiece per unit area can be calculated as follows :

$$\frac{I}{\text{area}} = \int \frac{F}{A} dt = \frac{1}{2} p T_0$$

where T = halfperiod - seconds

p = pressure nt/m²

I = impulse or momentum Kg m/s

unit area = m² , and

$\frac{1}{2}$ comes from integrating sin²

For the single turn coil used with the 9K joule bank the magnetic field per unit current can be calculated :

$$\theta = 45^\circ, \cos \theta = \frac{1}{\sqrt{2}}$$

$$I' = \frac{NI}{2b} = \frac{1 \times I}{1.27 \text{cm}} = 100 \text{KA} / 1.27 \text{cm}$$

$$B = \frac{4}{10} \frac{100 \text{KA}}{1.27 \text{cm}} \cdot \frac{1}{\sqrt{2}} = 70 \text{Kgauss per } 100 \text{ KA}$$

For every 100K amps of peak current from the capacitor bank this coil will produce a peak field of 70 K gauss.

For each of the five capacitor banks constructed during this experiment these calculations are as follows:

$$\text{Bank \# 1 } V = 20 \text{ KV}$$

$$E = 3 \text{K Joules}$$

$$T = 2.2 \text{ } \mu\text{s}$$

$$E = \frac{1}{2} cv^2 \therefore c = \frac{2E}{V^2} = \frac{2(3 \text{KJoules})}{(20 \text{KV})^2} = 15 \text{ } \mu\text{ farads}$$

$$Q = CV = (15 \text{ } \mu\text{f}) (20 \text{kv}) = .3 \text{ coulombs}$$

$$I_{avg} = \frac{2Q}{T} = \frac{2(.3 \text{ coulombs})}{2.2\mu s} = 273 \text{ K}_{amps}$$

$$I_{peak} = \sqrt{2} I_{avg} = 1.57(273 \text{ K}_{amp}) = 428 \text{ K}_{amps}$$

$$B_{max} = 428 \text{ k}_{amp} \frac{70 \text{ k}_{gauss}}{100 \text{ amp}} = 300 \text{ K}_{gauss}$$

$$P_{max} = \frac{(300)^2}{(100 \text{ kg})^2} \cdot \frac{6000 \text{ psi}}{2} = 54,000 \text{ psi} = 37.2 \times 10^7 \text{ nt/m}^2$$

$$\text{Impulse/m}^2 = \frac{1}{2} P T = .5(37.2 \times 10^7) 2.2\mu s = 409$$

Bank #2

$$E = 7.5 \text{ kgauss}$$

$$V = 5 \text{ kv}$$

$$T = 85\mu s$$

$$c = 600\mu \text{ farad}$$

$$Q = CV = (600\mu f)(5 \text{ kv}) = 3 \text{ coulombs}$$

$$I_{amp} = \frac{2Q}{T} = \frac{2(3)}{85\mu s} = 70 \text{ K}_{amp}$$

$$I_{peak} = \frac{\pi}{2} I_{amp} = (1.57) (70 \text{ K}_{amp}) = 110 \text{ K}_{amp}$$

$$B_{max} = 110 \text{ K}_{amp} = \frac{70 \text{ K}_{gauss}}{(100 \text{ K}_{amp})} = 77 \text{ K}_{gauss}$$

$$P_{max} = (77 \text{ K}_{gauss})^2 \cdot \frac{6000 \text{ psi}}{(100 \text{ K}_{gauss})^2} = 3600 \text{ psi} = 2.5 \times 10^7 \text{ nt/m}^2$$

$$\frac{I}{m} \sqrt{\frac{1}{2}} P T = \frac{1}{2} (2.5 \times 10^7 \text{ nt/m}^2) 85\mu s = 1060 \text{ nt-s/m}^2$$

-

Bank #3

$$E = 7.5 \text{ K Joules}$$

$$V = 5\text{KV}$$

$$Q = 3 \text{ coulombs}$$

$$T = 30\mu\text{s}$$

$$I_{\text{peak}} = \frac{\pi}{2} I_{\text{avg}} = (1.57) \frac{2(3)}{30\mu\text{s}} = 314 \text{ Kamp}$$

$$B_{\text{max}} = 314 \text{ Kax} = \frac{70\text{Kgauss}}{100\text{Kamp}} = 220\text{Kgauss}$$

$$P_{\text{max}} = (220\text{Kgauss})^2 \cdot \frac{6000\text{psi}}{(100\text{Kgauss})^2} = 29000\text{psi} = 20 \times 10^7 \text{ nt/m}^2$$

$$\frac{I}{\text{m}^2} = \frac{1}{2} PT = .5(20 \times 10^7)(30 \times 10^{-6}) = 3,000 \text{ nt-s/m}^2$$

Bank #4

$$E = 6\text{K}_J$$

$$V = 20 \text{ KV}$$

$$Q = .6 \text{ coulombs}$$

$$T = 3.1\mu\text{s}$$

$$I_{\text{peak}} = \frac{\pi}{2} \frac{2Q}{T} = \frac{\pi Q}{T} = \frac{(3.14)(.6)}{3.1 \text{ s}} = 608 \text{ Kamps}$$

$$B_{\text{max}} = 608\text{KA} \frac{70\text{KG}}{100\text{KA}} = 425\text{Kgauss}$$

$$P_{\text{max}} = (425\text{KG})^2 = \frac{6000\text{psi}}{100\text{KG}} = 108,000\text{psi} = 75 \times 10^7 \text{ nt/m}^2$$

$$I/\text{m}^2 = \frac{1}{2} PT = .5(75 \times 10^7)(3.1 \times 10^{-6}) = 1160 \text{ nt-s/m}^2$$

Bank #5

$$E = 9 \text{ KJoules}$$

$$V = 20 \text{ KV}$$

$$Q = .9 \text{ coulombs}$$

$$T = 6\mu\text{s}$$

$$I_{\text{peak}} = \frac{\pi}{2} \cdot \frac{2(.9)}{6\mu\text{s}} = 470\text{kamps}$$

$$B_{\text{max}} = (4.70\text{KA}) \cdot \frac{70\text{Kg}}{100\text{KA}} = 330\text{Kgauss}$$

$$P_{\text{max}} = (330\text{KG})^2 = \frac{6000\text{psi}}{(100\text{Kg})^2} = 65,000\text{psi} = 45 \times 10^7 \text{ nt/m}^2$$

$$I = \frac{1}{2} PT = .5(45 \times 10^7)(6 \times 10^{-6}) = 1350 \text{ nt-5/m}^2$$

It is now possible to make a simple estimation of the deformation to expect in a copper sample of given wall thickness assuming that all the energy transfer takes place during the first half cycle and that the wall thickness is much greater than the skin depth so that shielding is complete. During the pulse time the pressure in excess of the yield strength of the workpiece acts against the inertia of the wall mass to accelerate it to a velocity. After the pulse is over this initial velocity or momentum works against the mechanical strength of the workpiece until the wall comes to rest. If the pressure pulse is several times the yield strength then this is nearly equivalent to the deformation predicted by assuming that all the impulse is transferred to the workpiece instantly and provides an initial velocity which carries the wall to its final deformation against the yield strength.

For the case of .040" wall copper sample .0460" OD in the 9Kjoule Bank. The calculation is as follows:

wall mass per unit area = $LWT \rho/A$

$T = .040''$ wall thickness = .1cm

For unit meter $M = (100\text{cm})(100\text{ cm})(.1\text{cm}) 8.9\text{g/cc per m}^2$

$$M = 8.9\text{Kg/m}^2$$

σ max copper = 20,000psi

Assume dynamic yield strength = 2 times static yield strength

$$\bar{\sigma} = 40,000\text{psi}$$

$$\bar{\sigma} = \frac{pr}{T} \dots p_{\text{yield}} = \bar{\sigma} \frac{T}{V} = 40,000\text{psi} \cdot \frac{.040''}{.460/2} = 6956\text{psi}$$

$$= 4.8 \times 10^7 \text{ nt/m}^2$$

The impulse per meter square from the previous calculation for capacitor Bank #5 = 1350 nt-s/m^2

Therefore the velocity corresponding to this impulse or momentum is

$$I = mv \dots V = \frac{I}{m} = \frac{1350\text{nt-s/m}^2}{8.9\text{Kg/m}^2} = 152 \text{ m/s}$$

This assumes that the wall is accelerated to this velocity instantly against zero yield strength as if it were a free body mass. After the pulse this momentum works against the yield strength of the material until the wall comes to rest.

$$V = \sqrt{2As} \dots s = \frac{V^2}{2A} = \frac{V^2 m}{2F}$$

$$s = \frac{(152\text{m}\cdot\text{s})^2 (8.9\text{kg}/\text{m}^2)}{2 (4.8 \times 10^7 \text{nt}/\text{m}^2)} = 2.13 \times 10^{-3} \text{m} = .213\text{cm} = .080''$$

The actual measured deformation is the sample was only third of this or about .032". This is a result of the many simplifications and approximations and idealizations used in this analysis. However, it does give some idea of the magnitude of deformation to expect from this system. This example has been presented more to show how to analyze and predict the performance of the capacitor and coil system in order to arrive at the force time profile than as an example of how to solve the complicated mechanics of deformation problem to arrive at the deformation from force profile.

There are a number of factors which affect the accuracy of this analysis. Probably the most dominant one comes from the mechanics of deformation at extremely high strain rates. There is probably less than 20% error in estimating the applied pressure since the magnetic portion of the system is fairly well defined. However the ratio of dynamic yield to static yield stress may be many times greater than the factor of 2 used in this analysis. Furthermore, since the part is accelerated to 152m/s in 6 μ s the peak acceleration experienced by the workpiece is on the order of 1 million gravity. An acceleration of this magnitude is bound to set up stresses in the workpiece which further complicate the

analysis. In addition there has been no allowance for the energy that may have gone into elastic deformation or into shock wave energy since the pulse time is of the same order of magnitude as the transit time for sound waves around the part.

One additional consideration that has not been included in the analysis that does concern the capacitor coil system is the effect of the additional half cycles after the first. If the second half cycle has less than half of the amplitude of the first then it can usually be ignored. Also if the operation has already been completed during the first half cycle then successive half cycles will only produce additional heat. If additional half cycles do have an effect that can be added up individually or accounted for as follows.

In the case of a ringing discharge which lasts for several cycles before dying out, it is necessary to calculate the impulse imparted to the workpiece by those additional cycles after the first half cycle. Since the impulse is proportional to the pressure, which is proportional to the square of the current, each additional half cycle contributes only a fraction of the impulse imparted on the first cycle. Their fraction is equal to the square of the ratio of the peak current in that cycle to the peak current in the first half cycle.

If we let the ratio of the current peaks equal R then the ratio of the total impulse to that of the first half cycle is

$$\frac{I_T}{I_1} = 1 + R^2 + R^4 + R^6 = \frac{1}{1-R^2}$$

For the case of the 9 KJoule 20 KV bank the ratio of current peaks was found to be equal to .7 therefore the ratio of the total impulse in all half cycles to that in the first is

$$\frac{1}{1-R^2} = \frac{1}{1-(.7)^2} = 1.98$$

In order to check on the use of the standard skin depth approximation I constructed a simple inductance simulation experiment. I started with two copper samples, one .020 thick and one .040" thick wall copper tube, both .460" OD. I wound a number of turns of fine copper wire around the outside of each sample. Then I made a small search coil by winding wire around a plastic rod and inserting it within each sample. I connected the outer coil to a signal generator and the inner coil to an oscilloscope. With this arrangement I was able to measure the relative change in the field that penetrated the cylinder as a function of frequency. Starting with a very low frequency, the amplitude of the signal that penetrated was constant up to a certain frequency where the signal began to show a measurable attenuation. As the frequency was increased the amplitude of the signal that was able to penetrate the copper cylinder and be picked up by the search coil continued to decrease. I recorded the frequency at which the signal was reduced

to one-third of its original value and also the point where it reached 1/9 of its original amplitude. For the .020" sample attenuation began at 10KHz and reached one-third at 65KHz and 1/9 at 160KHz. For the .040" wall sample attenuation began at 20K and reached 1/3 at 155KHz and 1/9 at 375KHz. I considered the wall thickness to be equal to one skin depth at the frequency at which only 1/3 of the signal penetrated. This is compared with the skin depth thickness predicted at this frequency from the standard skin depth approximation.

$$S = .296 \sqrt{KT} \text{ where } K = \rho/\rho_C u$$

Half Period

T = miliseconds S = skin depth cm

at a frequency of 65KHz the half period is .0077 miliseconds

$$S_1 = .296 \sqrt{.0077(1)} = \sqrt{.025} \text{ cm} = .010"$$

at a frequency of .55KHz the half period in .0032 miliseconds

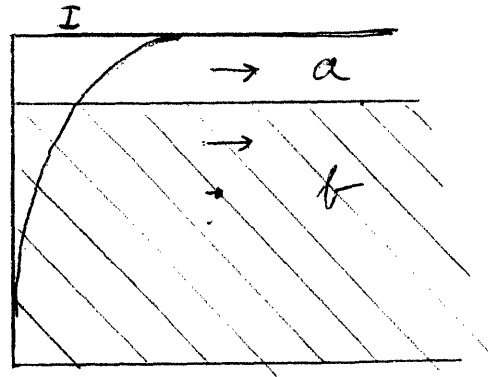
$$S = 296 \sqrt{.0032} = .016 \text{ cm} = .006"$$

This compares to the measured value of thickness of the copper tube necessary to shield out 2/3 of the field

$$\frac{.040"}{.010"} = 4 \quad \frac{.020"}{.006"} = 3.3$$

Therefore I conclude from this test that for the geometry of this experiment the thickness of copper wall necessary for efficient shielding is from 3 to 4 times as great as that calculated from the standard skin depth approximation.

There are two reasons for this result. First this geometry is a closed cylinder not an infinite flat sheet and second it is not an infinitely thick sheet but instead a surface only one skin depth thick. In an infinite thick sheet currents flow in both region a and region b as shown in the diagram at right. The current that flows in region b tends to cancel the field beyond region b. However,



they also have an effect on the current in region a. The presence of a current in region b will tend to increase the current in region a and therefore concentrate more current near the surface. When there is no metal in region b then there are no currents there and no enhancement of the surface current. Therefore, there is less shielding in a thin sheet than would be predicted by the infinitely thick sheet approximation for skin depth.

As a check on the calculated peak field it is possible to calculate the coil inductance and system inductance, and use them to compute the fraction of the capacitor energy which will appear in the leads and in the coil. From Montgomery's book on solenoids the inductance is given as²

$L = a, N^2 \theta(\alpha, B)$ where $\theta(\alpha, B)$ is a geometry factor from the graph of $\theta(\alpha, B)$ for $\alpha=1$ and $B=1$, a value is found for $\theta(\alpha, B) = 14 \times 10^{-9}$ henries. The coil radius is equal to .64 cm and for a one-turn coil $N = 1$.

$$L = a, N^2 \theta(\alpha, B) = .64\text{cm} (1)^2 (14\text{nh}) = 8.9\text{nh}$$

The system inductance is arrived at from the equation for the half period

$$T = N\sqrt{LC} \therefore L = \left(\frac{T}{\pi}\right)^2 \times \frac{1}{C} = \left(\frac{6\mu\text{s}}{\pi}\right)^2 \cdot \frac{1}{4\text{s}\mu\text{f}} = 81 \text{ nh}$$

Therefore the leads and switch and internal inductance of the capacitors must account for $81 - 8.9 = 72 \mu\text{h}$. The ratio of coil inductance to system inductance is $8.9/81 \approx 1/10$. Therefore, the peak coil energy should be $1/10$ of the total capacity energy of 9000 Joules or a coil energy of 900 Joules. The coil energy can be calculated from the current as follows.

$$E = \frac{1}{2} L I^2 = \frac{1}{2} (8.9 \text{ nh}) (470\text{KA})^2 = 980 \text{ Joules}$$

This agrees very well with the energy computed on the basis of inductance ratios. The energy can also be calculated from the peak field according to equations in Montgomery as³

$$B_{\text{max}} = \left(\frac{\mu}{a_1}\right)^{\frac{1}{2}} \phi(\alpha, B)$$

$$\mu = \frac{B^2 a^3}{[\phi(\alpha, B)]^2} \quad \text{where } \mu = \text{energy-Joules}$$

$a_1 = \text{radius -cm}$

$$\phi(\alpha=1 B=1) = 5.6 \times 10^{+3}$$

$$\mu = \frac{(330\text{KG})^2 \cdot (.64\text{cm})^3}{(5.6 \times 10^3)^2} = 910 \text{ Joules}$$

This compares very well with the value calculated above.

There is one additional consideration which effects the field which the coil produces for a given current. In the analysis the current distribution was assumed to be uniform along the axis. Since the pulse is fast the current distribution is effected by inductive factors in addition to being limited in its penetration to about one skin depth. The current distribution itself in such a way as to minimize the total field energy that it produces, which is the same as minimizing the inductance. The field energy and inductance are minimized when half of the current flows at each end of the coil. This creates two current filament loops separated by the coil length. In the single turn coil used in this experiment the coil length was equal to its diameter. Therefore, if the current flowed only at the ends of the coil the central field would be one-half of that predicted for a uniform distribution, and the maximum field near the end of the coil would be three-fourths of the central field for a uniform distribution. When the workpiece is inserted within the coil, the current distribution and coil inductance will be changed from what they are without the workpiece. The current distribution will be somewhat closer to a uniform distribution with the workpiece in place.

In order to make a direct measurement of the field produced by the single turn coil in conjunction with the 9K joule bank, I constructed a simple pick-up coil by wrapping five turns of fine wire around a .375" plastic rod. I connected this to a 20KV

oscilloscope probe which attenuated the voltage by 1000. By intergrating the voltage trace as follows I arrived at the peak measured B field.

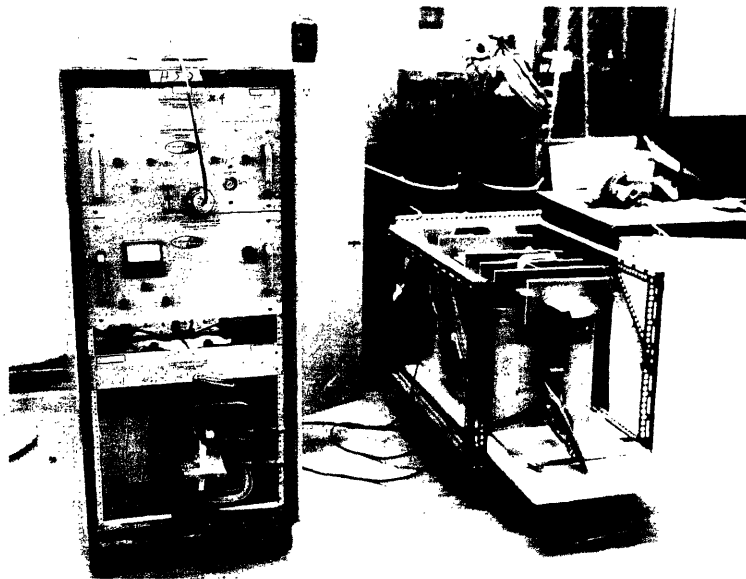
$$V = N \frac{d\phi}{dt} = NA \frac{dB}{dt} \therefore \int V dt = NA (B_{\max} - 0)$$

$$\int V dt = \frac{2}{\pi} \cdot V \cdot T_0 = \frac{VT}{\pi} \quad T_0 = \frac{T}{2}$$

$$B_{\max} = \frac{VT}{\pi NA} = V(5.3 \times 10^{-2}) \text{ kgauss}$$

The capacitor voltage and pick-up coil voltage are shown below with the measured and calculated field.

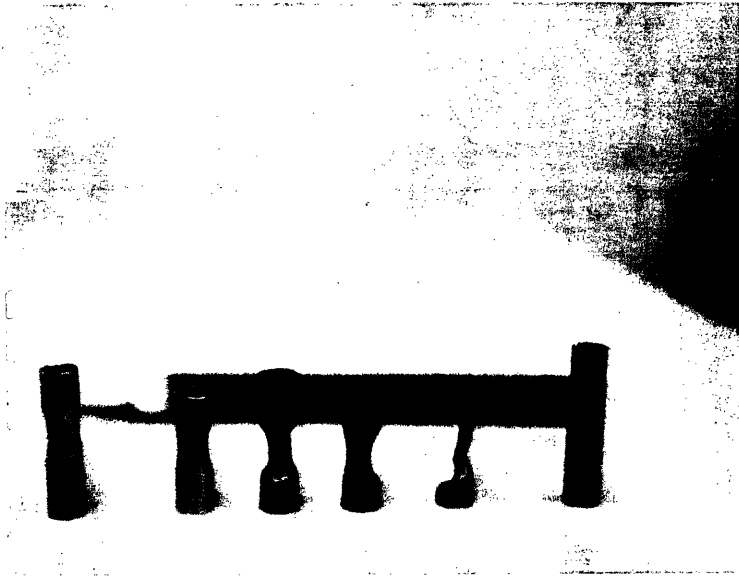
Capacitor kv	Pick up V	Measured B k gauss	Calculated B k gauss
2	400	21.2	32
4	900	47.7	65
6	1600	84.8	96
8	2400	127	131
10	3200	169	164



General view of experiment

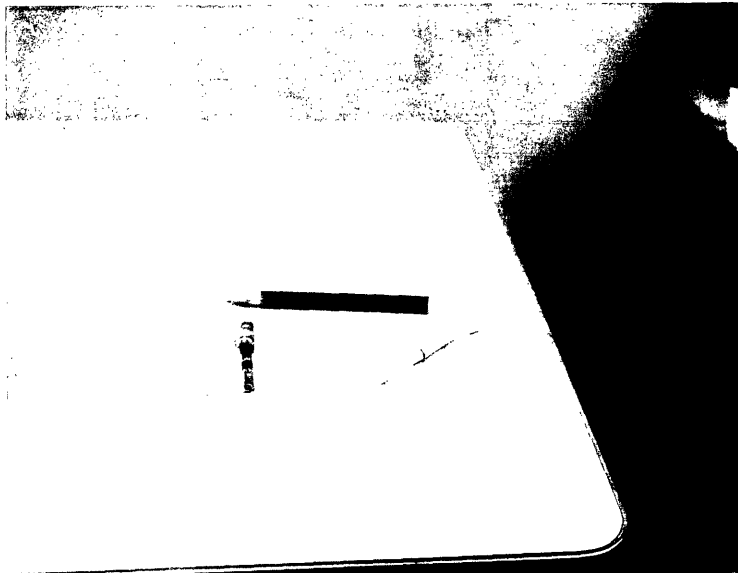
Close up of single turn coil

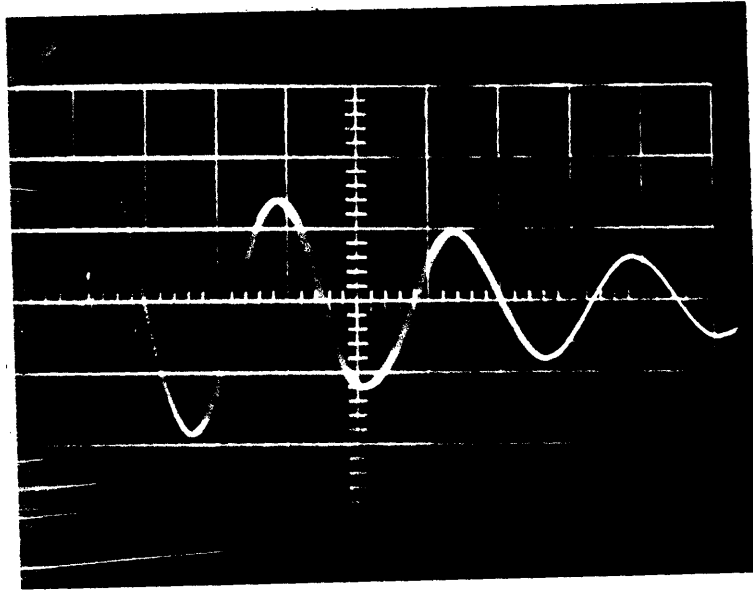




Samples made by magnetic forming

Inductance simulation coils and field probe coil





Typical voltage trace from pick up coil 1000 v/cm, 5 μ s/cm
capacitor voltage = 4 Kv

V. HISTORY

The history of pulsed magnetic metal forming spans less than 25 years and includes such early successes as the Magneform process developed to swage turnbuckles on the end of aircraft control cables. The symmetrical uniform high pressure of a pulsed magnetic swaging coil produced a cable termination that was free of the usual thin spots and stress concentrations associated with mechanical swaging. The process was so successful that it was approved in record time by the FAA for all aircraft cables and today is the standard process by which thousands of control cables are made. Another technique developed by Henry Kolm is the double pulse forming system developed to apply traction forces to test load bonded honeycomb structures. In this process a slowly rising magnetic field is allowed to penetrate the skin and then a reverse fast rising pulse is used to create a magnetic field pressure that pushes out from the blind side of the metal sheet. This in effect creates a new tool that has never existed before, a hammer which hammers out instead of in. The process has not found wide-spread application, however it is used to remove dents from aluminum airplanes.

Several other magnetic techniques were developed during the late sixties and early seventies. One of these was a process for shaping welded titanium honeycomb panels without crushing the honeycomb. This involved passing a large current pulse from an electrolytic capacitor through the two skins of the panel while it was in a background field of 60KG in a large 16" OD water cooled

magnet at the Bitter Magnet Lab. I worked on this project with Henry Kolm and Bob Weggel, however, the cost of capacitors and a superconducting magnet for a full scale system would have made the process uneconomical and the technique was not pursued.

During this same time period I worked with Henry Kolm on a process to magnetically inject liquid metal into a mold. Initial experiments used wood^smetal, a low melting temperature lead alloy, with approximately the same resistivity of steel. These initial experiments were very successful and indicated that it might be possible to make a steel injection molding machine by this technique. However the high cost per part for capacitor stored energy and numerous political problems with funding prevented the research from being continued.

The work that provided the greatest impetus for the research I am presently involved in was the work of T. J. Morin and others with a company known as Industrial Magnetics, Inc. in the late sixties.⁴ They developed a process called hydrodynamic welding for joining tubular shapes of similar and dissimilar metals. Their system used RF induction heating to preheat the workpiece to a high temperature before a magnetic pulse squeezed the parts together. With this technique they were successful in welding even vastly dissimilar alloys in the laboratory. However problems with reproducibility in the production environment and management problems within the company prevented the system from finding widespread application.

Some more recent work is being done at Maxwell Labs in California.⁵ They are presently developing and testing a magnetic technique for making end closure welds on nuclear reactor fuel rods. They are using a 40K Joule capacitor bank operating up to 50KV into a single turn coil. Their coil can produce fields up to 750Kgauss with a rise time of 1-1/4 μ s. Presently, they are using a thick walled driving sleeve to collapse the thin walled fuel rod tube against the end plug with sufficient velocity to cause impact welding. They have tried operating the system without the driving sleeve, however because the tube is so thin and resistive it would require an extremely fast pulse to be effective against the thin walled tube alone. Even operating at 50KV, they have not been able to make a capacitor bank with sufficient energy which will still create that fast a pulse. The system operating with the driving sleeve has been very successful to date and has a good chance of being used commercially to weld reactor fuel rods.

VI. CONCLUSIONS

There are a number of conclusions that I have arrived at from my work with magnetic forming systems. First and foremost is that there seems to be no great difficulty in working at the 20 KV level if one uses reasonable care in the design and many thin plastic sheet instead of transformer oil immersion.

In the area of pulse coil design, I have arrived at the following perspective. A single turn coil has the lowest possible inductance and the greatest strength. Because it has the lowest inductance it should be able to achieve a fast pulse even with a higher capacitance, lower voltage capacitor bank. However, since part of the energy is wasted in lead and switch inductance and resistance it is important to consider the trade offs carefully. A multiturn coil has a higher inductance and therefore requires a higher driving voltage to create a fast pulse. However, with many turns and lower current the switch and lead losses are less. Of the multiturn coil construction, the machined helix appears to have the greatest advantages from the standpoint of strength. However, for longer duration pulses where heating of the inside lip of the coil is a problem or where low coil resistance is important, it may be possible to achieve advantages with a tape wound as a filament wound coil. When making a tape wound coil it is important to remember that the current in this type of pulse coil will tend to flow at the edges of the tape in the same way that the current in a single turn coil tends to flow at the two ends. For long slender

coils or coils requiring the minimum resistive losses, it may be necessary to use a filament wound structure to force the current to flow in a uniform distribution throughout the coil cross section. It is important to remember that the coil feels about the same pressure as the workpiece and therefore high pressure forming systems require very strong coil construction.

All magnetic forming systems rely on an energy storage system and associated switching to deliver the necessary pulsed energy. The traditional approach uses high voltage capacitors and either ignitrons or spark gaps. The high cost of capacitors places a severe restraint on which magnetic processes can be economically competitive with existing methods.

There are a number of new developments in pulsed energy storage that may help to eliminate this problem in the near future. These include the homopolar generator, the pulsed compensated alternator, and the storage inductor. Each system replaces the problems of bulky expensive capacitors with other problems particular to that device. A storage inductor requires a complicated vacuum breaker and communicating capacitor arrangement that is often as large and costly as the inductor itself. It remains to be seen if the systems can be developed to deliver a fast enough pulse for metal forming.

Another device that may become useful is the homopolar generator (Faraday disk generator). Present systems deliver large

current large energy pulses (>50. m joules) with a long pulse time (7.1 sec). It may be possible to make smaller homopolar generators perhaps with air core magnets, that should produce fast enough pulses for metal forming.

The newest and most promising energy source in the pulsed compensated alternator developed by a group in Austin, Texas. Because of the low inductance due to the compensating winding the alternator delivers a pulse of several M joules at thousands of volts in less than one millisecond.

The pulsed compensated alternator also has the advantage that the current is automatically forced to go through a zero current point after each half cycle. Therefore the rotor does not have to come to rest before repeating the cycle as is the case with the homopolar generator. If smaller alternators with faster pulse times can be developed, then the repetition rate of this device may make it the prime candidate for a metal forming pulse supply.

On the subject of contact resistance, I have concluded that the most practical approach is to use silver paste or other conductive paste to fill the irregularities in any mechanical connection which is required to carry a large current pulse. This approach appears to work considerably better than using extremely high pressure on clean copper surfaces.

I have arrived at the following rather controversial

conclusion concerning grounding of a high voltage capacitor system. I have developed a preference for floating the entire high energy portion of the system at the ends of two sets of charging resistors for the positive and negative leads. By floating the capacitor and enclosing them within an insulating box and isolating the firing circuit either mechanically or optically, it is possible to greatly reduce the chances of dumping the large capacitor energy outside of the enclosure. It is still a good idea to place a grounded cage around the insulating enclosure as a final safety measure. If one side of the capacitor were to be grounded then there are certain fault conditions which will be likely to dump a large current pulse into the ground cable. Because of the inductance of the ground circuit this current pulse may momentarily raise part of the ground circuit to a dangerously high voltage.

One final conclusion may possibly be drawn from this work, although much more experimentation and analysis will be required to determine the trade-offs. If a capacitor system can be built to have a very high Q (low damping) and an extremely fast ringing frequency, then it may be possible to use the same capacitor over and over again, many times within a single forming cycle by allowing the capacitor to ring with the coil. This approach may turn out to be more efficient in coupling the expensive capacitor energy into the workpiece.

REFERENCES

1. D. Bruce Montgomery, Solenoid Magnet Design, Wiley-Interscience, New York, 1969, p.2.
2. Ibid, p.200.
3. Ibid, p.200.
4. T. J. Morin and John Zotos, Welding Cast Iron to Steel Comes of Age, Foundry, December 1969.
5. F. Brown, J. Bandas, and N. T. Olson, Magnetic Welding of Breeder Reactor Fuel In End Closures, Welding Journal, June 1978.

BIBLIOGRAPHY

1. Frederick W. Grover, Inductance Calculations, Dover Publications, Inc., New York 1945.
2. E. T. Bruno, High-velocity Forming of Metals, ASTME, Dearborn, Michigan, 1968.
3. Behavior of Metals Under Impulsive Loads, Dr. John S. Rinehart and John Pearson, Dover Publication, Inc., New York 1954.
4. Hansjorg Jansen, Some Measurements of the Expansion of a Metallic Cylinder with Electromagnetic Pulses, IEEE Transactions on Industry and General Applications, Vol. IGA, 4 No. 4 July/August 68.
5. Simon Foner and Henry H. Kolm, Coils for the Production of High-Intensity Pulsed Magnetic Fields, The Preview of Scientific Instruments, Vol. 28, No. 10, 799-807, Oct. 1957.