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**Design and Calibration of a Ferromagnetic Torsion Balance**

Oliver W. Moen
DESIGN AND CALIBRATION
OF A
FERROMAGNETIC TORSION BALANCE

by
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A Thesis
Submitted to the Department of Metallurgy
in Partial Fulfillment of the
Requirements for the Degree of
Bachelor of Science in Metallurgical Engineering

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ACKNOWLEDGEMENT

The ferromagnetic torsion balance was constructed by Elliot Willner in 1951.

The apparatus, as given to me, was in need of a furnace, water coolers for the poles, light source, alignment of the torsion wire, hot sample holder and over all compactness. This was accomplished with the help of Dr. F. A. Hames and Dr. E. Roberts, the work being done at the Montana School of Mines Machine Shop. The report was written with the help of Ralph Smith and Mrs. Blanche Fleming.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Additions to and Redesign of the Apparatus</td>
<td>5</td>
</tr>
<tr>
<td>Tube Furnace</td>
<td>5</td>
</tr>
<tr>
<td>Temperature Measurement</td>
<td>6</td>
</tr>
<tr>
<td>Temperature Control</td>
<td>6</td>
</tr>
<tr>
<td>Hot Sample Holder</td>
<td>7</td>
</tr>
<tr>
<td>Coolers for the Poles</td>
<td>7</td>
</tr>
<tr>
<td>Optical System</td>
<td>8</td>
</tr>
<tr>
<td>Direct Current for the Electromagnets</td>
<td>9</td>
</tr>
<tr>
<td>Mechanical Alignment of the Upper-suspension Wire</td>
<td>9</td>
</tr>
<tr>
<td>Calculation of Size of Suspension Wire</td>
<td>10</td>
</tr>
<tr>
<td>Assembly of Balance</td>
<td>12</td>
</tr>
<tr>
<td>Experimentation</td>
<td>12</td>
</tr>
<tr>
<td>Experiment One</td>
<td>12</td>
</tr>
<tr>
<td>Permeability of 1085 Steel</td>
<td>13</td>
</tr>
<tr>
<td>Permeability of Nickel</td>
<td>13</td>
</tr>
<tr>
<td>Experiment Two</td>
<td>13</td>
</tr>
<tr>
<td>Curie Point of 1085 Steel</td>
<td>14</td>
</tr>
<tr>
<td>Curie Point of Nickel</td>
<td>14</td>
</tr>
<tr>
<td>Bibliography</td>
<td>27</td>
</tr>
</tbody>
</table>

## FIGURES, GRAPHS AND PLATES

### Figures

1. Tube Furnace                                                        15
2. Water Coolers                                                       16
3. Light Source                                                        17
4. Assembly of Units                                                   18
5. Wiring Diagrams                                                     19

### Graphs

1. Calibration of Furnace                                              20
2. Permeability of 1085 Steel and Nickel                              21
3. Curie Point 1085 Steel                                             22
4. Curie Point Nickel                                                 23

### Plates

1. Complete Unit                                                      24
2. Furnace and Water Coolers                                          25
3. Light Source and Powerpac                                         26
INTRODUCTION

Magnetic materials can be divided into three major groups: diamagnetic, paramagnetic and ferromagnetic. From a magnetic point of view, the ferromagnetic are the most interesting. Ferromagnetic materials include the elements iron, nickel, cobalt, certain of the alloys of these elements and a group of alloys first studied by Huesler. These latter are ferromagnetic largely because of the presence of manganese in special combination with the other non-ferrous elements.

Faraday demonstrated that materials possess magnetic properties in different degrees. Iron, cobalt, and nickel, when placed in a field of magnetic forces not only aligned themselves parallel to the magnetic field but also became strongly magnetized. Other materials, paramagnetic and diamagnetic, will assume positions parallel or perpendicular to the field and are weakly magnetized. Those that assume parallel positions are paramagnetic, while those assuming perpendicular positions are diamagnetic. The paramagnetic and diamagnetic materials are of little practical value for magnetic applications and are generally referred to as nonmagnetics.

Measurement of magnetic moments can be made by observing the force on a small sample which is suspended
between poles of an electromagnet designed to give a field of uniform gradient in the direction of the polar axis.

If \( F \) is the force exerted on the specimen in the direction of the polar axis, \( I \) the magnetic moment per unit volume of the sample, \( \frac{dH}{dx} \), the rate of variation of magnetic field strength along the polar axis of the magnet, and \( V \) the volume of the sample, then it can be shown that

\[
F = I \frac{dH}{dx} dV
\]

If the sample is composed of several phases of magnetic moments \( I_1, I_2, \ldots, I_n \) and volumes \( V_1, V_2, \ldots, V_n \), the equation becomes

\[
F = \frac{dH}{dx} + (I_1 dV_1 + I_2 dV_2 + \ldots + I_n dV_n)
\]

When the field strength is sufficiently high throughout the sample to cause magnetic saturation of the ferromagnetic phases, the paramagnetic and diamagnetic phases present can be neglected because their influence is small. The various ferromagnetic moments, \( I_1, I_2, \ldots, I_n \) can be considered as a single constant characteristic of the amount of the ferromagnetic phase present. This comes as a result of the fact that the shape of the poles are such that \( \frac{dH}{dx} \) is a constant value for the volume occupied by the sample. Considering that the volume of the principal ferromagnetic phase is large compared to that
of the other paramagnetic components present the equation becomes

\[ F = \frac{dH}{dx} I V \]

Where \( V \) is the volume of the principal ferromagnetic phases of magnetic moment \( I \).

For a given specimen at a given temperature, \( V \) would remain constant, so if \( F \) is to change, then \( \frac{dH}{dx} \) (and therefore \( I \)), must change. This type of variation can be called saturation magnetization which is a volume property. In this type of measurement, the \( \frac{dH}{dx} \) is changed by changing the current through the coil. In changing the current the field strength \( H \) is changed also. The field strength \( H \) is the number of lines of force per sq. cm. Only the field strength of the area where the sample is located needs to be considered. \( I \) is related to \( H \) by a permeability curve for a given metal at a given temperature.

If a sample is diamagnetic the lines of force will diverge around the sample, since the air is more permeable than the sample material. In this case, the permeability

is less than one and the magnetic moment acts to rotate
the specimen perpendicular to the field. If a paramag-
etic sample were used some of the lines would be con-
centrated in the sample giving a magnetic moment I for
a given field strength. If the field current were
plotted against the restoring force which is equal to F,
the graph would be a linear relation in which the perme-
ability is greater than one. A ferromagnetic sample
will concentrate more lines of force through it than will
a paramagnetic sample. The permeability is also a func-
tion of the field strength applied and at infinitely
large field strengths the permeability is one and mater-
ial has reached the saturation point.

The Curie temperature is that temperature at which
a ferromagnetic material becomes paramagnetic. This is
a structure sensitive property and can be changed by
changing the composition of the material or the fabri-
cation treatment. These treatments would effect the
Curie temperature by either raising or lowering it.
When making a Curie temperature curve, a field strength
should be used such that the portion of the permeability
curve for the material being tested is linear, or nearly
linear. In this circumstance, the change in magnetic
moment is due almost entirely to the change in magnetic
properties at the Curie point.
The first construction was an electric tube furnace which was built around a quartz glass tube four inches long with a one-half inch inside diameter. The heating coil was wound with 22 gauge chromel wire with a resistance of 1.04 Ohms per foot. To produce an even heating coil it was wound on a lathe using an iron bar whose diameter was 1/4 inch smaller than the outside diameter of the quartz tube. This produced a coil with a smaller diameter than the quartz tube. When the coil was put on the quartz tube, it was under tension causing it to stay in place. The poles being one inch apart restricted the amount of insulation on the furnace. Over the coil was wound a layer of 5/8 inch asbestos tape. This in turn was covered with a seamless woven asbestos hose the length of the furnace. The ends of the poles and also the asbestos covering could be painted with aluminum paint which would help keep the poles cool and act as a binder for the asbestos while serving as further insulation for the furnace.

The asbestos is held in position on the furnace at three points. A copper wire is used at the front, while the center and back are held by brass clamps which also act as electrical contacts for the furnace. The brass
clamp in the middle is further used to hold the furnace in place between the poles of the magnets. The clamp is insulated from the frame of the magnet by two pieces of formica and a plastic washer. The furnace can be removed by loosening a thumb-nut and removing the outside formica disc. (See Figure 1 and Plate 2).

TEMPERATURE MEASUREMENT

A chromel-alumel thermocouple is inserted in the rear of the furnace. It is held in place by two hard asbestos washers. The chromel-alumel thermocouple was calibrated with a platinum-rhodium thermocouple, the junction of platinum-rhodium thermocouple was held in the furnace at the sample position giving readings on a potentiometer in millivolts. (See Figure 1).

TEMPERATURE CONTROL

The source of power for the furnace is a 110 volts ac line using a powerstat to control the voltage and thus the temperature of the furnace. In the calibration of the chromel-alumel thermocouple a temperature of 1933 F was reached with a power setting of 40 volts. The maximum temperature for the furnace was not reached in that 1933 F is sufficient for most work, but higher temperature could be reached with a larger voltage setting without injury to the furnace. (See Graph 1).
HOT SAMPLE HOLDER

A hot sample holder was made from a 1/8 inch quartz glass tube with a copper clip to hold the sample. The sample holder is held in place by a thumb screw.

COOLERS FOR THE POLES

Water coolers for the poles were the only solution to keep the poles cool when the furnace is run at high temperature over a long period of time. The coolers were made at the Montana School of Mines Machine Shop using a cast brass bushing stock eight inches long, 2\(\frac{1}{2}\) inches in diameter with a one inch hole through it.

Since the poles of the electromagnets are different in size, 1 1/8 and 1 1/2 inches in diameter, two different sizes of water cooler were necessary. The water coolers were made by first making two spools with the respective inside diameters of the poles. The outside diameters of the spools are 1 5/8 and two inches respectively with a wall thickness of 1/8 inches. One-half by 1/8 inch rings were made to fit the respective spools. The rings were tapped on opposite sides and copper pipes 1/8 inch by one inch long were inset in the rings and soldered in place. The copper tubes serve as the inlet and outlet of each cooler. The rings were fitted over the spools and a bead of solder was run around the two sides.
The two faces of the coolers were resurfaced by the use of a belt sander. The coolers were found to be watertight when tested. (See Figure 2 and Plate 2).

OPTICAL SYSTEM

The optical system of the original apparatus was not satisfactory and was completely redesigned. The optical system is used to restore the sample to a set position between the poles of the magnets so that the restoring force is equal to the magnetic moment of the sample.

The sample is positioned by reflecting a beam of light, from a mirror that is mounted on the sample arm assembly, to a ground glass scale. The ground glass scale and a single filament light bulb are mounted in a varnished oak box. The light bulb is connected to a 3½ volt transformer which in turn is connected to a 110 volt ac source.

The lens was mounted in a piece of plastic and secured to the frame by two 1/8 inch brass bolts. The lens is used to gather the light from the mirror and focus it in a sharp thin line on the ground glass scale. The ground glass scale is divided into 1/8 inch divisions. When the beam is focused on the center line, the sample is in the set position (midpoint between the two poles). (See Figure 3 and Plate 3).
DIRECT CURRENT FOR THE ELECTROMAGNETS

The power for the coils of the electromagnets is furnished by a 110 volt ac source. The ac voltage is regulated by a powerstat thus regulating the amount of direct current from a powerpac which is connected to the coils. A second oak box was made similar to the one made for the light source. The powerpac's frame was made smaller so as to fit inside the box.

It was found later that a steadier current could be obtained through the coils of the magnets if the powerpac were operated on 110 volts ac or line voltage, without the powerstat. The powerpac was built to operate at 110 volts ac which would give a 525 volt reading at the direct current leads. The amount of current through the electromagnets could be regulated by a variable 2,500 to 10,000 ohms resistor giving an approximate maximum and minimum current of a 150 and 50 milliamps respectively. (See Figure 3 and Plate 3).

MECHANICAL ALIGNMENT OF THE UPPER SUSPENSION WIRE

On the original apparatus the specimen holder would move with a circular motion making a circle of about 1/8 inches in diameter. This effect gave incorrect readings because the sample was not in a set position due to the movement of the sample between the poles at the time readings were made. This error was eliminated by the
use of a small screw type chuck to insure that the upper suspension wire is held in the center of the rotating shaft.

The shaft was also given a throw by an improper spring in that all the compression force was put on one side of the rotating shaft instead of distributing the force equally over the circular collar which is the top support of the shaft.

A new spring was made with this in mind. Brass washers were made to keep the spring centered at all times in relation to the rotating shaft. Care was taken to give the same gear clearance at all points. If this were not done it also would produce an unbalanced force causing movement of the sample in a back and forward direction with respect to the fixed position.

A new upper and lower suspension wire were used to insure stability of the sample. The wire diameters can be calculated as shown below.

**CALCULATION OF SIZE OF SUSPENSION WIRES**

The proper diameters of the suspension wires depend on the magnetic moment of the sample and the accuracy required.

Between the poles the magnetic gradient is nearly constant but increases slightly as the sample moves toward
the smaller pole. In order that the specimen be stable between the magnet poles, the rate of increase of the restoring force produced by the torsion balance, must exceed the rate of increase of the magnetic force or

\[ \frac{d}{dx} \left( F_1 + F_2 \right) > \frac{dF}{dx} \]

\[ \frac{1}{L^2} \left( \frac{d}{d\theta} F_1 L + \frac{d}{d\theta} F_2 L \right) \frac{dF}{dx} \]

\[ \frac{1}{L^2} \left( T_1 + T_2 \right) \frac{dF}{dx} \]

where

- $F_1$ equals the restoring force caused by the rotation of the upper portion of the suspension.
- $F_2$ equals the restoring force caused by the lower portion of the suspension.
- $T_1$ equals the torsion constant of the upper portion of the suspension wire.
- $L$ equals distance from the specimen to the torsion wire.
- $dF/dx$ equals the rate of change of the magnetic force with distance along the axis of the pole at the position of the sample.

After the diameter of the upper portion of the suspension wire is chosen to give the required accuracy for specimens which will require a restoring force between the limits $F_1$ and $F_2$, the diameter of the lower wire of the suspension can be calculated from the given relation.\(^1\)

\[ \text{---} \]

1. Ibid. pp. 226-227
ASSEMBLY OF THE BALANCE

The balance was made a compact unit by mounting the various parts on a piece of 3/4 inch plywood 16 by 52 inches. The unit was rewired and as much wiring as possible was put under the plywood panel to make it neat and to make operations more convenient and easy.

Before the coils and light source were secured, the sharpest line possible was obtained on the ground glass scale by adjusting the light source box.

The boxes and board were stained, shellaced and varnished to give a bright finish which is easy to keep clean. (See Plate 1 and Figures 4 and 5).

EXPERIMENTATION

Experiment One.

The hot sample hold was tested for magnetic moment and produced a flat line when plotting restoring force versus milliamps, through the coils. This showed that there will be no effect due to the sample holder in future operation.

The object of the first experiment is to obtain graphs of the permeability of 1085 hot-rolled steel and pure nickel: A specimen was cut to the following dimensions; diameter 3/32 inches and length 1/4 inches; weight .163 grams. The sample was put in the hot sample holder which in turn was secured in position in the sample arm.
assembly. The furnace was put over the sample and adjusted to make sure that the sample was clear of the furnace walls.

The current through the coil was started at 0, and was varied in 25 milliamps intervals up to 200 milliamps. The change in the restoring force was read on the red scale of the restoring force dial and a graph of milliamps versus scale readings were plotted in graph number two. Due to the high permeability of the steel and because the maximum current through the coils, 150 milliamps will not produce sufficient field strength to saturate the steel, the upper proportion of the curve could not be obtained.

The nickel sample weighing .049 grams and 1/16" square gave a permeability curve (graph number two) which resembles a paramagnetic substance in that the graph is a straight line with a permeability greater than one. This is due to the fact that only the first part of the curve is obtained because of the low maximum field strength.

Experiment Two.

Curie points for the two samples, 1085 steel and the pure nickel, mentioned in experiment one were obtained in the following manner. The samples were put in the holder in the same manner as before. This time the
amperage through the coils was held constant at 150 milliamps while the temperature of the furnace was changed.

The temperature of the furnace was run up to 900 F for the nickel and 550 F for the steel.

First a cooling curve was run by cutting down the current to the furnace (by steps). Then a heating curve was run by increasing the current in the same manner. The heating curves were started at 600 F for nickel and 300 F for the steel, which are also the terminating temperatures for the cooling curves. Readings were taken from the red scale with the sample in its set position in the center of the poles, at temperature intervals of 20 F. This is done by directing the reflected beam to the center line on the ground glass scale by means of the dial at the time the readings were taken.

The Curie temperature for the 1085 steel is shown by graph number three. The Curie temperature for the pure nickel is shown by graph number four.

Curie points for different materials can be obtained with little difficulty in the future with the use of this apparatus.

**********
FIGURE I

A SUPPORT          E BRASS CLAMPS
B ASBESTOS TAPE    F ASBESTOS WASHER
C ASBESTOS TUBING  G COPPER WIRE CLAMP
D QUART GLASS TUBE H THERMOCOUPLE LEADS

I COIL
FIGURE 2

A  RING
B  SPOOL
C  RUBBER HOSE
D  HOSE CLAMP
E  INLET
F  OUTLET
G  COPPER TUBES
LIGHT SOURCE
POWERPAC
1/4 SCALE

FIGURE 3

A LIGHT SOURCE
A 3-OUTLET PLATE
B INLET 110 VOLTS
C OUTLET 110 VOLTS
D GROUND GLASS SCALE
E BRASS SHIELD
F SINGLE-FILAMENT LIGHT

B POWERPAC
A 2-OUTLET PLATE
B INLET TO COILS
C INLET TO FURNACE
D OUTLET 110 VOLTS
ASSEMBLY OF UNITS
1/8 SCALE

A. Plywood Panel  E. Mirror
B. Powerpac       F. Torsion Balance
C. Light Source   G. Furnace
D. Brass Shield   H. 34 1/2 inches

Figure 4
FIGURE 5

A  TO  COILS
B  TO  FURNACE
C  OUTLET  110  VOLTS
D  INLET  TO  POWERPAC
E  INLET  TO  FURNACE
F  OUTLET  AND  INLET
   110  VOLTS
CALIBRATION OF FURNACE

DEGREES FAHRENHEIT CALCULATED FROM PLATINUM RHODIUM THERMO

GRAPH NO. 1
PERMEABILITY
AT 70F

MA THROUGH COILS

GRAPH NO. 2

1085 STEEL

NICKEL
CURIE POINT

1085 STEEL

GRAPH NO. 3
CURIE POINT
NICKEL

COOLING
HEATING

GRAPH NO. 4

-23-
PLATE 1

A LIGHT SOURCE
B POWERPAC
C TORSION BALANCE
FURNACE AND WATER COOLERS

PLATE 2
A FURNACE
B WATER COOLERS
LIGHT SOURCE AND POWERPAC

PLATE 3

A LIGHT SOURCE
B POWERPAC

2. STANLEY, J. K., Metallurgy and Magnetism, American Society for Metals, Cleveland, Ohio, 1948.