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The Construction of a Ferromagnetic Torsion Balance

Elliott Willner

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THE CONSTRUCTION OF A FERROMAGNETIC TORSION BALANCE

by

Elliott Willner

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

MONTANA SCHOOL OF MINES
Butte, Montana
May 1, 1951
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ACKNOWLEDGEMENT

The construction of the apparatus was performed entirely in the machine shops at the Montana School of Mines. The materials utilized in the construction were obtained through the courtesy of many sources: the A. C. M. Co., the Montana Power Co., and the Western Iron Works.

I wish to acknowledge the invaluable assistance and guidance rendered to me by Dr. F. A. Hames, without whom the construction and operation of the balance could not have been achieved; and I also appreciate those services rendered to me by Mr. George Harmon of the Physics Department. I also wish to acknowledge the aid of Mr. Richard Corin of Williams Studio, who made possible the reproduction of the plates contained herein. Lastly, I wish to express thanks to my wife for her loyal devotion and understanding in seeing that this task was undertaken with the proper attitude.
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GLOSSARY OF SYMBOLS

I -------- Intensity of magnetization is equal to the magnetic moment per unit volume.

σ -------- Specific intensity of magnetization is equal to the magnetic moment per gram.

H -------- Field strength of the electromagnet (oersteds).

dH/dX --- Rate of change of field strength with distance across gap (oersteds per inch).

T -------- The torque that is developed upon a specimen which is suspended on the arm of the torsion balance (dyne-cm).
THE CONSTRUCTION OF A FERROMAGNETIC TORSION BALANCE

INTRODUCTION

There are known to science only four ferromagnetic elements: iron, nickel, cobalt, and gadolinium. Some of the oxides of these elements are also ferromagnetic and possess similar magnetic characteristics. In addition, a group of alloys containing nonmagnetic elements, known as Heusler alloys, have ferromagnetic properties; these alloys contain manganese, copper, and aluminum.

The construction of a ferromagnetic torsion balance was undertaken with the object in mind of using the device as a means for detecting ferromagnetic phases. The magnetic properties of which are influenced by structural changes caused by varying conditions in production, composition, and structural properties.\(^{(2:82)}\)

The essential parts of the apparatus would include 1) an electromagnet to produce a strong magnetic field with a uniform gradient in the direction of the polar axis, and 2) a mechanical and optical system in which a torsion balance is employed to measure the relative force on the sample. A third part that could be constructed at some future date would be a furnace with auxiliary apparatus to measure and control the temperature.
THEORY

The fundamentals of ferromagnetism are described in the literature. Similarly, the theory which applies to the operation of the torsion balance has also been described in detail. (3:224)

When a ferromagnetic sample is suspended between poles of the electromagnet it is acted upon by the magnetic field and in turn develops a magnetic moment. If this magnetic moment is determined per unit volume, the value is the "intensity of magnetization" (I) of the specimen. Similarly, the magnetic moment per gram is the "specific intensity of magnetization" (σ).

The force (f) on a ferromagnetic specimen is directly proportional to the mass (m) of the specimen; the specific intensity of magnetization (σ) of the specimen; the field strength (H) and the rate of variation of magnetic field strength along the polar axis of the magnet (dH/dX):

\[ f = m\sigma H dH/dX \]

The sketch which follows illustrates how a sample, when suspended on the arm of the torsion balance, develops a torque (T) which is directly proportional to the force (f).
Similarly, the number of divisions (n) on the circular scale of the apparatus presents values directly in proportion to the torque exerted upon the specimen:

\[ n \propto T \propto f = m\sigma H dH/dX \]

In utilizing the instrument, a ferromagnetic specimen (e.g., Ni) of known \( \sigma \) and mass is measured; that is, the number of divisions on the scale is recorded. Therefore

\[ n_{Ni} \propto T_{Ni} \propto f_{Ni} = m_{Ni} \sigma_{Ni} H dH/dX \]
Then to analyze an unknown \( u \) ferromagnetic substance, the mass of it can be determined as well as \( n_u \), which is directly proportional to the force, \( f_u \).

\[
n_u \propto T_u \propto f_u = m_u \sigma_u \frac{HdH}{dX}
\]

then

\[
\frac{n_u}{n_{Ni}} = \frac{T_u}{T_{Ni}} = \frac{f_u}{f_{Ni}} = \frac{m_u \sigma_u \frac{HdH}{dX}}{m_{Ni} \sigma_{Ni} \frac{HdH}{dX}}
\]

Therefore

\[
\sigma_u = \frac{n_{u}m_{Ni} \sigma_{Ni}}{n_{Ni}m_u}
\]

Hence, the unknown \( \sigma \) can be determined, which value is desired for the comparison of the ferromagnetic specimens. If the field is sufficiently strong to saturate the specimen, then the measured \( \sigma \) is the specific saturation intensity of magnetization.

An application of the torsion balance is found in determining the presence of a phase which was not present before or after treatment.
The detection of magnetic properties and the extent to which they occur are indicative of changes within a metal. For example, upon cooling from elevated temperatures, carbon steel undergoes a phase transformation from the nonmagnetic austenitic phase to the magnetic ferrite. With proper manipulation of the apparatus (after installation of the furnace) the start of transformation to the ferritic phase could easily be determined. Needless to say, there are many applications of the apparatus at room temperature.

CONSTRUCTION

The Electromagnet: The coils of the magnet, as well as their housing were supplied by Dr. Hames, all that remained to be completed in the Magnet Assembly, Figure 1, were the fabrication of the soft-iron cores and plates to pass over the cores in order to prevent the coils to move horizontally.

The design for the pole faces was arrived at by taking the average ratio of dimensions that were utilized in the construction of similar apparatus by Carapella, Wulff, Fereday, and Hames. The cores were turned down to size and tapped for installation. Copper plate was
utilized for the coil stops.

**Torsion Balance:** The design for the torsion balance was taken in part from Buehl and Wulff. Because of the necessity for fitting the apparatus to the coils, modifications were made (Figure 2). The entire balance (except the indicator dial, drive gear, spring, some screws, and the torsion wire) is made of brass and bronze stock. Brass and bronze were used so that any extraneous magnetic influence on the field between the coils would be eliminated.

**Details:** Figure 3. The upper chuck was made of bronze stock. The double set of 4-40 screws serve satisfactorily for the purpose of locking the ends of the torsion wire. The chuck was force fitted into the iron gear.

Bronze bearings were also force fitted into the brass plates for the standard supports and the lower spindle assembly. The bearings were made for the purpose of presenting an area for sturdier support for the spindles than would have been realized from the plates alone.

The dial-shaft assembly is composed of four parts: the drive gear, the shaft, the dial, and the knob. The iron drive gear was force fitted onto the brass shaft,
MAGNET ASSEMBLY

SCALE - 1/2" = 1"

FIGURE 1

MONTANA SCHOOL OF MINES LIBRARY
BUTTE
Side View of Balance
Note the details of construction.
CIRCUIT DIAGRAM OF POWER PACK

FIGURE 4
which in turn was pinned into the bronze knob. The dial is made of lucite plastic. The back of the dial was divided into one-hundred divisions, and a card with numerals in decade were printed for readings in either direction of rotation and was secured to the dial as well as the knob.

The standards were turned down from bronze stock. The standards were drilled 3/4 in. above the control plate because at that dimension the dial-shaft gear rests upon the upper gear and spring, which is under 5 lb compression caused by the tension in the torsion wire. The two standards were aligned and reamed to assure true bearing surfaces for the shaft.

The dial-shaft stop was fitted to the dial-shaft in order to secure the shaft in one position with a tolerance of horizontal movement of 1/16 in.

The sample-arm assembly is made up of six parts: the sample holder, the arm and wire holder, the counterbalance and screw shaft, the dash-pot and its shaft, an elbow for connecting the counter-balance shaft to the dash-pot shaft, and finally, a mirror for the optical system (Figure 5) was glued to the elbow.

The sample arm is made up of the actual specimen holder, a screw to secure the specimen in the holder,
a shaft to connect the specimen to the torsion wire holder, and finally a nut to lock the specimen holder to the connecting shaft. All materials are made of brass.

The sample arm and torsion wire holder is made of two separate parts which are held together by means of the screw-shaft of the counter-balance. The sample arm holder is bored in order to permit the sample arm shaft to slip inside and fit snugly. A screw may be used to lock the shaft in the arm. The torsion wire holder is bored through and fitted with two double sets of 4-40 screws for locking the upper and lower wires in position. The purpose of the upper and lower wires is to prevent any whipping-back that might be experienced with the use of a single fiber. Apparently, the upper wire of smaller dimension, provides the needed sensitivity, whereas the lower wire prevents the so-called whipping back.

The counter-balance weight is made of bronze and is set on its brass screw-shaft. At the end of the screw-shaft is an elbow which supports a shaft connected to a dash-pot made of magnesium. The dash-pot shaft is connected to a brass piece which was force fitted into
the magnesium cup. Finally, a mirror is glued to the elbow.

The lower spindle is made of bronze and is fitted with a double set of screws for locking the lower torsion wire in place. The spindle passes through a bearing to another plate fitted with a screw to lock the spindle in place.

All the parts were assembled and mounted on a brazed brass-angle support, which in turn was secured to the framework of the electromagnet. Piano wire of various dimensions are at hand for the torsion fiber. At present, an upper suspension of .008 in. diameter and a lower wire of .015 in. diameter have been installed. The dash-pot was immersed in a 100 cc beaker half-filled with oil.

In order to supply the direct current to the electromagnet at 150 ma, a power pack had to be constructed. The circuit diagram is shown in Figure 4. In addition, the power pack is connected to a Variac, which is used to closely control the current passing through the coils.

**Optical System:** The purpose of the optical system is to provide a method for determining the zero or starting point of each observation with some degree of accuracy. The system (Figure 5) operates as an optical
OPTICAL SYSTEM

SCALE - 1-1/2" = 12"

FIGURE 5
Upper: Arrangement of Apparatus
Lower: Apparatus in Operation
lever; that is, the relatively large distance between the scale and the mirror permits a sensitive control over the position desired.

The specific dimensions of this system were arrived at experimentally. A lens was found to be necessary to focus the filament line on the scale. This lens is mounted on a wooden platform which sits on top of the beaker of oil. The lens is best utilized about 3/8 to 1/2 in. in front of the mirror.

A wooden box was made to support the operating assembly and to provide means for the proper height of the mirror for its position in the optical system. In addition, for compactness, the box also houses the power pack.

CALIBRATION

A series of tests was made to determine approximately the most satisfactory size of the specimens to be used; the best position of the specimen between the pole gaps; the gradient of flux along the polar axis; the saturation values and comparison of iron and nickel specimens; and the relative effect on sensitivity of the variation in diameter of the torsion wire. Some determinations were
Graph #1

Determinations of Size Ratio of Specimens

- Fe - Diam. 0.1"
- Fe - Diam. 0.04"
- Ni - Diam. 0.08"
- Ni - Diam. 0.04"

Divisions per Gram

Ratio - Length: Diameter
GRADIENT DETERMINATION #1

Fe-Armco #125 ma
.015" upper wire
.030" lower wire

Horizontal Position

Vertical Position

Distance of Center of Sample from Small Pole

Graph #2

- 22 -
Gradient Determination #2

Divisions Per Gram

.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
(inches)

Distance of Center of Sample from Small Pole

Graph #3
SUSCEPTIBILITY OF SAMPLE HOLDER

Graph #4

DECENTERING

Graph #5
made without the aid of the Variac, and the use was
made of a power pack borrowed from the Physics Department
prior to the construction of the power pack now
employed.

**Size:** Samples of iron and nickel were prepared
for determination; they were cut to varying lengths
and to two diameters, and weighed. The results of the
preliminary analysis indicated that a maximum value for
all specimens would be obtained from those which had a
ratio of length to diameter of over 4:1, and those
specimens of a small diameter: .04 in. for Fe and Ni;
less magnetic specimens can be slightly larger (Graph 1).
Moreover, the length of the specimens to be used are
specified upon analysis of the gradient curves.

**Gradient & Position:** The force gradient between
poles (Graphs 2, 3) indicates a steep slope. Analysis
of the slope indicates that specimens exposed in the
field of this gradient will have a variation of 1000
divisions per gram for each .03 in. of length.
Therefore, specimens should be kept as small as possible,
meet length-diameter ratio, and of utmost importance,
be placed in the same position in the field in order
to obtain consistent and comparative results.
Holder: In order to determine the susceptibility of the sample holder in the field, a test was made of the empty holder in the field under varying flux conditions. A typical curve showing the susceptibility of the holder is shown in Graph 4. Dependent upon the position of the holder between poles, the susceptibility will vary; therefore, a test should be made before each set of determinations in order to correct the readings. In addition, as determined by the position of the holder in the field, it was noticed that the sample holder will be attracted to the pole which presents the strongest flux density.

Decentering: Evidently, the decentering of the sample holder in the vertical plane has little if no effect on the position of a specimen (Graph 5).

Standardization: An effort was made to standardize the apparatus against accepted values for iron and nickel. Specimens of these metals were subjected to varying conditions of flux, but the field between the poles was not strong enough to bring the iron to full saturation. Apparently, the nickel specimen was approaching this level. The data for the Fe-Ni is not comparable because the forces exerted upon them were not in the
region of standard saturation comparison; that is, the saturation-level ratio of Fe to Ni is 3.98 to 1, whereas the maximum ratio found with the apparatus was 3.1 to 1 and then the ratio declined sharply with a decrease in flux. Apparently, the magnetic field which is created is not strong enough to saturate the iron (Graph 6.)

**Sensitivity:** The same specimen was analyzed with upper suspension wires of .015 and .008 in. in diameter. The sensitivity, as indicated by the number of divisions per gram, for the .008 in. wire was found to be 200 times greater than that of the .015 in. wire. This degree of sensitivity has made the apparatus suitable for the relative comparison of the slightly magnetic Heusler alloys.

**OPERATION**

Preparation of the sample should be made according to the nature of its ferromagnetic properties. The size and shape of weakly magnetic specimens is not too critical; however, the relationships developed herein should be adhered to. Highly ferromagnetic materials should have their corners and edges ground so that the
specimen will approximate an ellipsoid. (3:225)

Because of the steep flux gradient between poles, the length of the specimen should not be over 1/4 in.; for if longer, undue precision would be necessitated in positioning the samples in order to achieve comparative results.

The weighed sample is then placed into the sample holder with caution to center the specimen. The holder is then placed into the housing on the torsion wire. Securing the arm with the screw provided in the housing has been found to be of little value. The specimen is then placed in a position which is to be referred to in all analysis. Naturally, for comparable results, the same position should be used for all operations. It is recommended that the center of the specimen be 1/2 in. from the small pole face. This distance may be found with the aid of calipers and a micrometer.

Once the desired position has been found, the lens in front of the mirror can be adjusted to find the "zero point" on the scale -- a more awkward method is to move the scale housing to the zero point.

Before turning the power on, a reading should be made on the upper or red scale on the dial; which will read directly the number of divisions of force on the
EFFECT OF MAGNETIZING FORCE ON IRON AND NICKEL

Graph #6

24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0

20
40
60
80
100
120
140
160

Divisions per Gram

Iron

Nickel

Graph #6
torsion wire that will be required to balance the specimen in the magnetic field. (In order to move the arm to the right, the dial is rotated to the right.) The power pack is then turned on, followed by an increase of power from the Variac until a maximum steady current of 150 ma is developed. If the specimen is strongly magnetic and comes in contact with the face of the pole piece, it will be well to bring the specimen holder to the center of the gap with one hand and turn the dial so that the subsequent torsion on the wire will balance the specimen in that region, then a final adjustment can be made to the zero point. The red scale is then read again, and the total number of divisions of force or torsion calculated. To make corrections for any magnetic influence exerted by the sample holder, a blank run should be made as mentioned elsewhere in this report.

Caution should be exercised in recording the number of dial divisions. If the sample requires a torsion of more than 100 divisions, the number of complete revolutions of the dial should be carefully observed, else error will definitely be incurred. To check the force exerted upon a specimen by the magnetic field, the power may be shut off after the balancing value
is obtained; followed by reading the lower or black scale. Then the specimen is repositioned, and the values obtained should check very closely with the initial observation.

Another word of caution, the current should be allowed to come to a definite steady flow before readings are taken. The samples slowly come under the influence of the magnetic field, and a short time interval is necessary to allow the sample, the coils, and the power pack to come to stable conditions; all of which can be judged with the observation of a steady maximum current flow.

CONCLUSION

The apparatus seems to be applicable to measurements of weakly magnetic phases. Unfortunately, the field of the electromagnet is not strong enough to saturate iron, so all observations cannot be referred to as standard values. Perhaps if iron samples were prepared under various conditions of heat treatment, the saturation value might be achieved.

The accuracy which is realized with the use of the apparatus is entirely dependent upon the operator:
positioning the specimen, zeroing the holder, allowing
time for complete development of forces, and exercising
care in recording all values. The precision of the
instrument with regard to reproduction is of the order
of 1 division in 100.
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