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ENGINEERING EVALUATION OF BARKHAUSEN EFFECT STRESS MEASUREMENT INSTRUMENTATION FOR APPLICATION TO AUTOFRETTAGED GUN TUBES

C. Gerald Gardner

Southwest Research Institute

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C. G. GARDNER
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78284

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Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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13. ABSTRACT

A limited preliminary evaluation was made of the potential of the ferromagnetic Barkhausen effect stress measuring instrumentation for monitoring residual stresses induced in gun tubes by autofrettaging. Experiments conducted on small scale tubes verified that the instrumentation is proportionately sensitive to stress induced by autofrettaging. Measurements made on a full scale 175 mm gun tube before and after autofrettaging gave unexpected anomalous results. Further investigation will be required to determine the cause of this result. Measurements made on finished 175 mm and 8-inch gun tubes indicated that the instrumentation is capable of distinguishing between tubes which have been autofrettaged and comparable tubes which have not. The results are judged to be sufficiently favorable to warrant further, more comprehensive evaluation of the instrumentation on gun tubes.

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FORWARD

Thanks are due the personnel of the Quality Assurance Directorate of Watervliet Arsenal, especially Mr. J. Penrose, for cooperation in conducting the work reported here.

The project benefited significantly from the technical supervision of Mr. R. H. Brockelman of the Materials Testing Division, Army Materials and Mechanics Research Center.

The technical assistance of Mr. G. A. Ferguson of Southwest Research Institute is acknowledged.

This report covers work performed under the first phase of the project. In the second phase, a portable, shopworthy Barkhausen effect stress measurement instrument, with parameters optimized for application to the 175mm gun tube, was fabricated and delivered to the Army Materials and Mechanics Research Center.

This project has been accomplished as part of the U. S. Army Manufacturing Methods and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques or equipment to insure the efficient production of current or future defense programs.

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INTRODUCTION

Certain military gun tubes are mechanically overstrained (autofrettaged) to induce a beneficial distribution of residual stress which permits higher chamber pressures than would otherwise be acceptable, and results in improved fatigue characteristics. Autofrettaging procedures in current use include swaging by forcing through the tube a sliding mandrel which is of larger diameter than the original bore diameter; and internally pressurizing the tube hydraulically. In either case the goal is to plastically enlarge the diameter of the tube so that when the applied load is removed residual hoop stresses exist with the outer fibers being in tension and the inner fibers being in compression. The radial extent of the plastically deformed zone may be anywhere between the inner bore radius (zero percent autofrettage) and the outer bore radius (100 percent autofrettage). Details regarding the autofrettage principle and its application to gun tubes may be found in References 1 and 2.

The usual method whereby uniformity of results from autofrettaging is controlled is by monitoring the tangential strain of the outer surface of the tube during and after the process; this is accomplished with strain gauges coupled to compliant hoops which encircle the tube, and can be attached and removed by means of buckles. Once removed, however, the strain gauges cannot be used to determine the extent of overstrain or, indeed, whether or not a given tube has ever been autofrettaged. Hence some method is needed for nondestructively detecting and evaluating the condition of overstrain, especially for checking tubes the manufacture of which may not be under direct Government surveillance.

Although X-ray diffraction can be used to measure residual lattice strains, its use requires considerable skill both in execution and interpretation; the apparatus is inconvenient for shop use; and the procedure is somewhat time consuming. A more convenient approach is therefore desirable.

An instrument which is a potential candidate for this application has recently been developed at Southwest Research Institute. The instrument is based on the stress dependence of the ferromagnetic Barkhausen effect, and previous results obtained with the instrument suggested that it should generally meet the autofrettage monitoring requirement. The present project was undertaken as a preliminary evaluation of this instrument for this application.

The evaluation, which was of limited scope, comprised two major tasks: the first task was, using small scale autofrettaged tubes as specimens, to verify that the Barkhausen effect stress measuring instrument was indeed proportionately sensitive to residual stresses induced by mechanical overstraining; the second task was to conduct limited tests of the performance of the instrument on actual autofrettaged gun tubes. The first task was conducted at Southwest Research Institute; the latter was conducted at Watervliet Arsenal. The primary gun tube involved in the project was the 175 mm M113E1 which is presently manufactured at Watervliet Arsenal. Some auxiliary measurements were also made on 8-inch howitzer tubes.

DESCRIPTION OF THE BARKHAUSEN EFFECT STRESS MEASUREMENT INSTRUMENT

Most of the magnetic characteristics of a ferromagnetic specimen are strongly influenced by mechanical stresses. However, only a few of these characteristics have been shown to be conveniently measured and correlated with the state of stress. One such characteristic is the Barkhausen effect, i.e., abrupt, localized "jumps" in the magnetization. Such jumps in the magnetization are accompanied by corresponding rapid changes in the magnetic induction field within and surrounding the material. A coil of wire placed in the field experiences an induced electromotance (voltage) proportional to the rate of change of magnetic flux through the coil; this noise-like "signal" may be amplified, electronically processed in various ways, and recorded. To induce Barkhausen jumps, a time-varying magnetic field may be applied by some external source. Figure 1 is a schematic diagram showing an elementary scheme for producing and recording signals produced by the Barkhausen effect. Various characteristics of the inductively produced "Barkhausen noise" signal are influenced by the state of mechanical stress of the test specimen. A review of the Barkhausen effect and its dependence upon stress may be found in References 3, 4 & 5 and prior references cited therein.

Various approaches to the design of a practical stress measuring instrument based on the Barkhausen effect are possible; a patent broadly covering such instruments has been issued to Southwest Research Institute (Reference 6). Figure 2 is a block diagram of the essential components of a practical instrument. In the version of the instrument used in this project, the "raw" Barkhausen signal is electronically processed to yield a signal which is a measure of the intensity of the Barkhausen signal. Figure 3 shows an example of a signal processed in this manner, the ordinate is proportional to the processed signal amplitude, and the abscissa is proportional to the magnetic field applied to the specimen.

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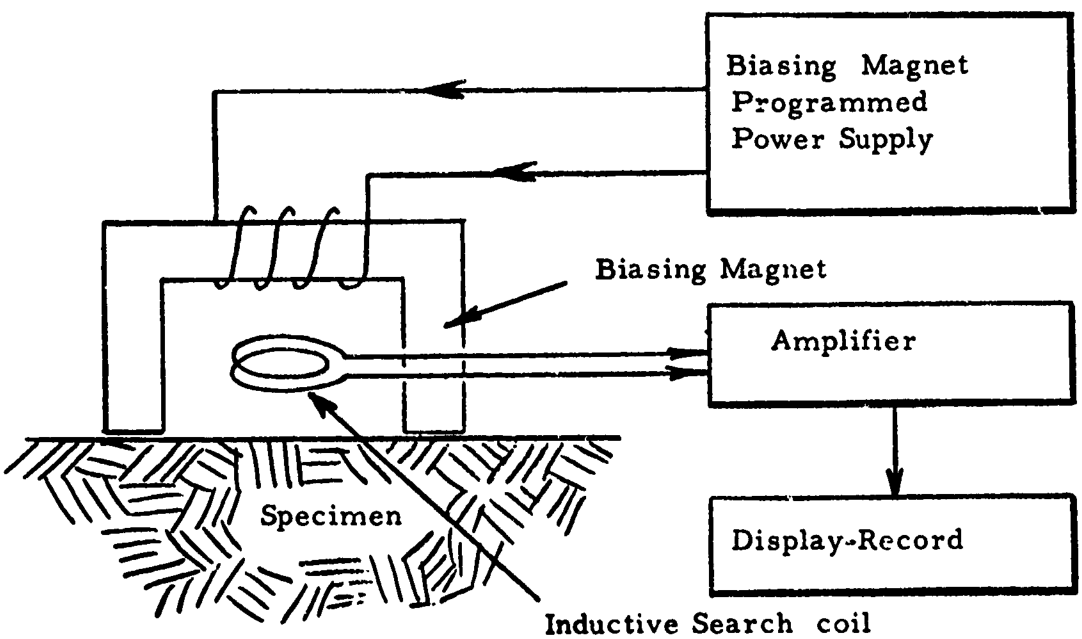

FIGURE 1. SCHEMATIC DIAGRAM OF THE ESSENTIAL FEATURES OF AN ARRANGEMENT FOR INDUCTIVELY SENSING THE BARKHAUSEN EFFECT.

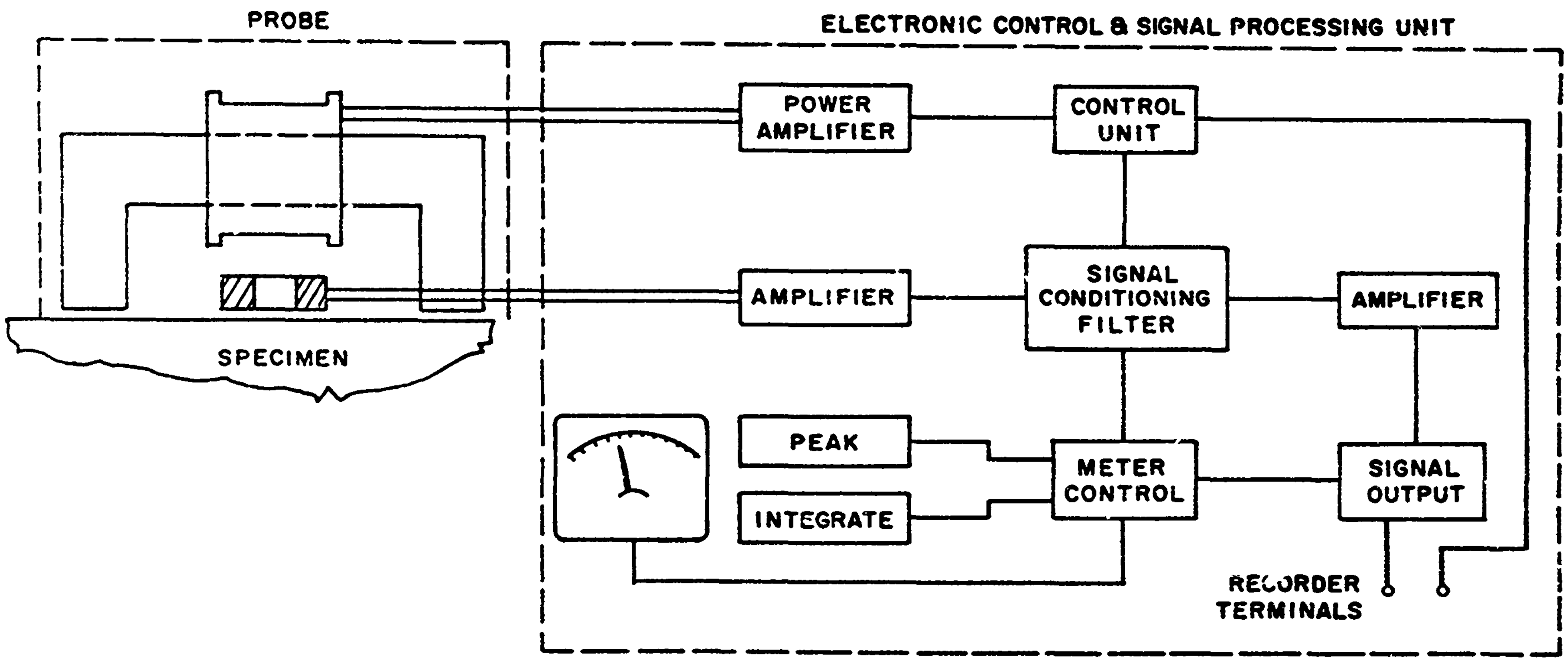

FIGURE 2. SCHEMATIC DIAGRAM OF ESSENTIAL COMPONENTS OF STRESS MEASURING INSTRUMENT BASED UPON THE STRESS DEPENDENCE OF THE BARKHAUSEN EFFECT.

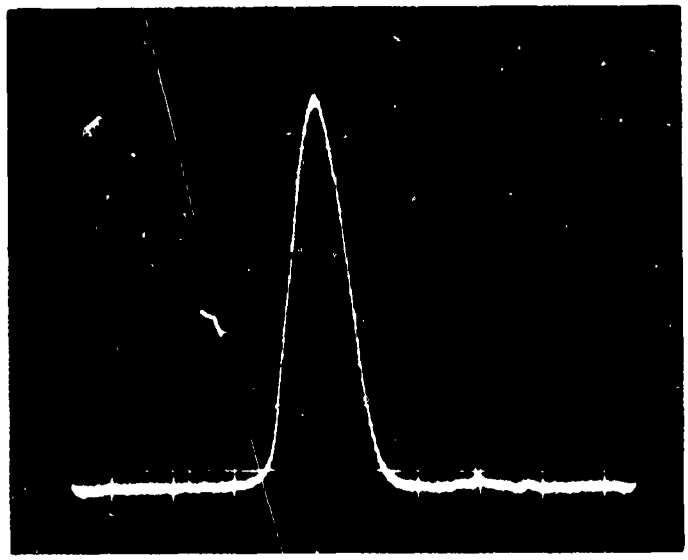

FIGURE 3. OSCILLOGRAPHIC RECORDING OF BARKHAUSEN EFFECT SIGNATURE OBTAINED DURING ONE REVERSAL OF SPECIMEN MAGNETIZATION. AISI 4340 specimen, stress relieved.

This signature varies in both general shape and amplitude as the state of stress of the specimen is varied. It has been empirically established that for most ferromagnetic steels the parameter of the signature which best correlates with stress is the peak amplitude. In the instrument used in this project, this peak amplitude was electronically measured and displayed on an analog meter.* With respect to its value for an unstressed specimen, the peak amplitude has been found to increase monotonically when the specimen is under tensile stress, and to decrease monotonically when the specimen is under compression, for most structural steels; the response of present instruments saturates at stresses of approximately $\pm$50 Ksi. For quantitative use, the instrument must be empirically calibrated using a specimen of the specific alloy in question, to which known loads are applied. Figure 4 is a representative empirically determined response curve.

The depth from which Barkhausen jumps can be effectively detected depends upon the constitution and geometry of the specific specimen and the design of the sensory probe, but is 5 to 10 mils at most; hence the stress that is sensed is essentially the surface stress.

For specimens in uniaxial tension, the maximum signal is obtained when the magnetizing yoke and the axis of the sensory coil are parallel to the tensile axis. For uniaxial compression, maximum signal occurs when the stress axis is orthogonal to the yoke and sensory coil axis. Complex stress distributions are more difficult to analyze.

EXPERIMENTS ON SMALL SCALE AUTOFRETTAGED TUBES

Introduction

Two experiments were conducted to demonstrate that the Barkhausen effect stress measurement instrument could discriminate between various intensities of residual stress induced by autofrettaging. The specimens used in the experiments were obtained from a commercial source, and consisted of a set of three small AISI-4340 tubes, 2-5/8 inch

*Another parameter sometimes measured is the integral of the signature, essentially the area under the curve in Figure 3. This is the "integrate" mode shown in Figure 2. In general, the "integrate" mode is a less sensitive indicator of stress than the "peak" mode.

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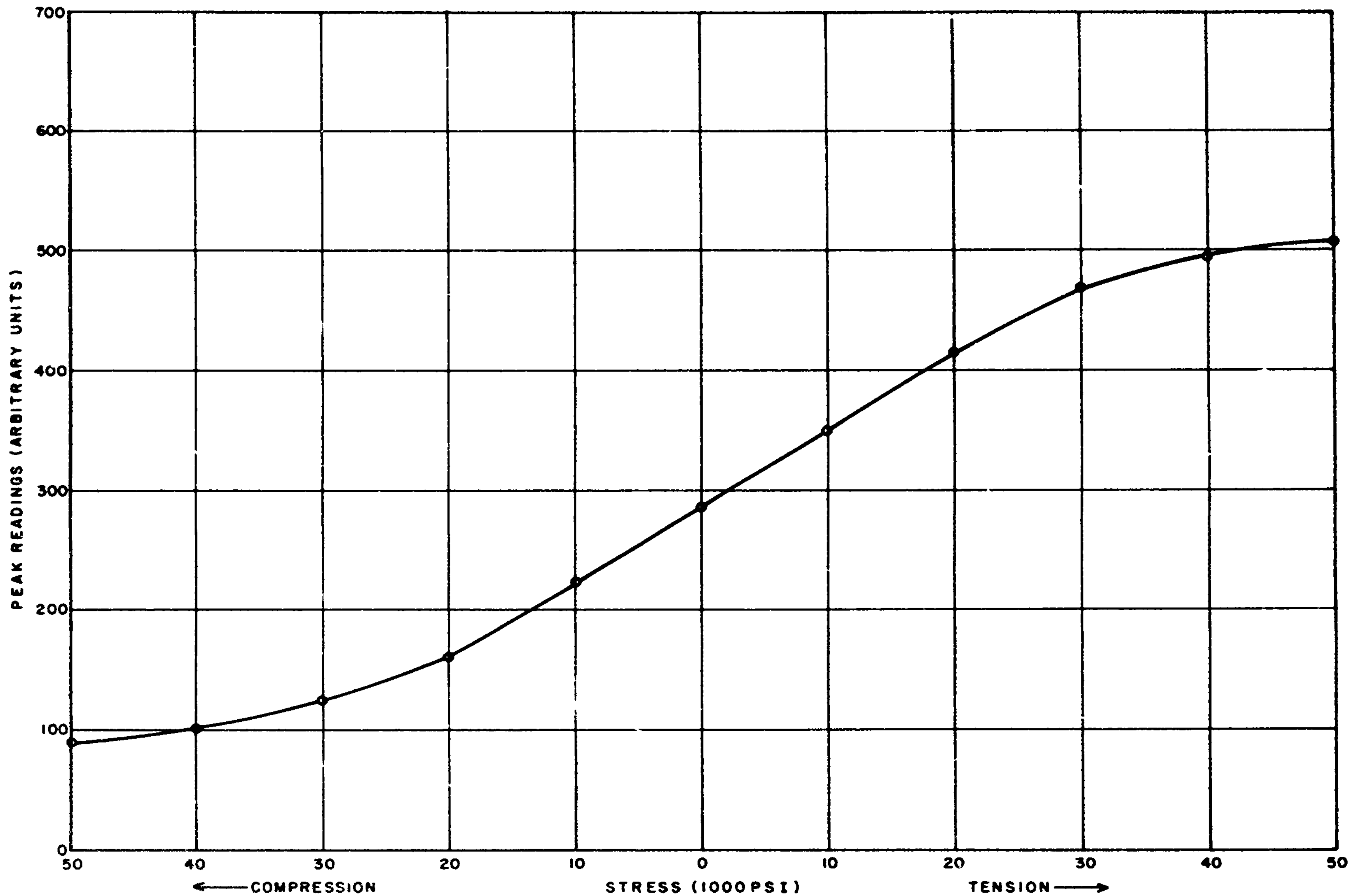


FIGURE 4. EMPIRICALLY DETERMINED CALIBRATION CURVE OF A RECENT IMPROVED VERSION OF THE BARKHAUSEN EFFECT STRESS MEASUREMENT INSTRUMENT. AISI 4340 steel specimen in cantilever bending.

in diameter, 8 inches long and with a 1 inch bore. These had been autofrettaged to respectively greater permanent tangential strain.

Prior to autofrettaging the tubes had been stress relieved for two hours at 1050°F and air cooled. Longitudinal and tangential strain gauges were applied to the specimens, and they were then hydraulically autofrettaged in a so-called "open-end" fixture, i.e., without imposing longtitudinal stress. The permanent tangential strain induced in the three tubes was 50, 140, and 505 microinches/inch, respectively.

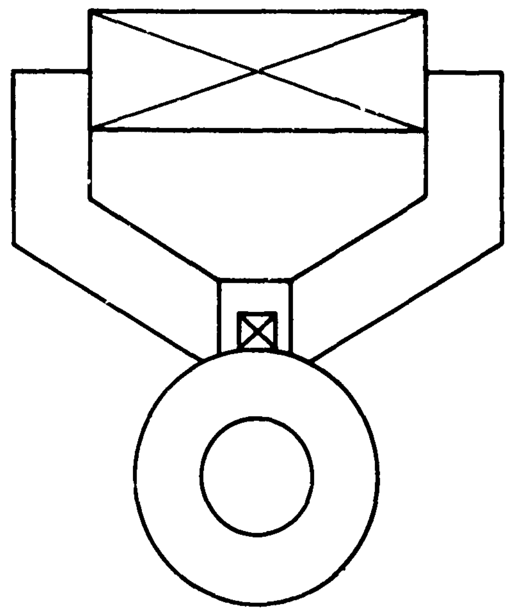
The first experiment consisted of simply making Barkhausen effect readings at prescribed points on the outer surface of each of the three tubes, and comparing results. (Although it would have been of great interest to compare Barkhausen effect measurements made on the bore surface of the three specimens, this was impossible (with existing instrumentation) because of the smallness of the bore size.) In the second experiment, the tube with the largest permanent strain was bored out in successive stages, so as to progressively relieve the tensile stress in the outer surface. Barkhausen effect readings and strain gauge readings were made at each stage of the boring operation. The progressive strain relief of the outer surface was obtained from the strain gauge data, and the results compared with the corresponding Barkhausen data.

A special magnetic yoke was used to make Barkhausen effect readings. The yoke was provided with two sets of pole tips, one set configured to fit the tube with the yoke oriented longitudinally, and the other set configured for the tangential (i.e., circumferential) orientation. Figure 5 is a drawing of the experimental arrangement.

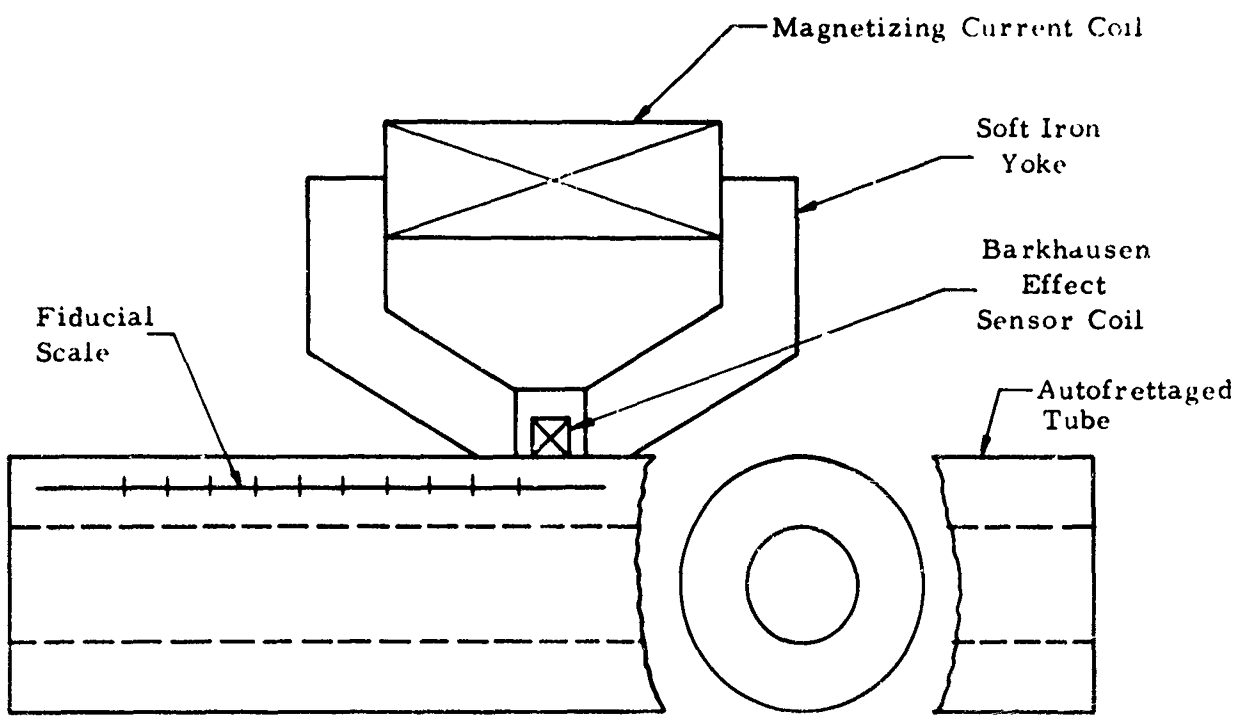
Comparative Measurements on Tubes with Different Amounts of Overstrain

A grid of reference points was stenciled onto the surface of each of the specimens; the probe was positioned with respect to these reference points. For each tube, Barkhausen effect readings were made at 1/4-inch intervals along four longitudinal lines situated at 90° intervals around the tube. The results are summarized graphically in Figures 6 and 7.

In Figures 6 and 7, each point plotted represents the average of five successive readings made at the same location on a cylinder (because of the essentially random nature of the Barkhausen effect, such averaging is necessary; it has been found that the average of five or more readings is reliably repeatable). One notes that there are substantial variations in the readings made at different points on the surface of each specimen. Since



Tangential Arrangement



Longitudinal Arrangement

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FIGURE 5. SCHEMATIC OF EXPERIMENTAL ARRANGEMENT FOR MAKING BARKHAUSEN EFFECT MEASUREMENTS ON SMALL TUBES.

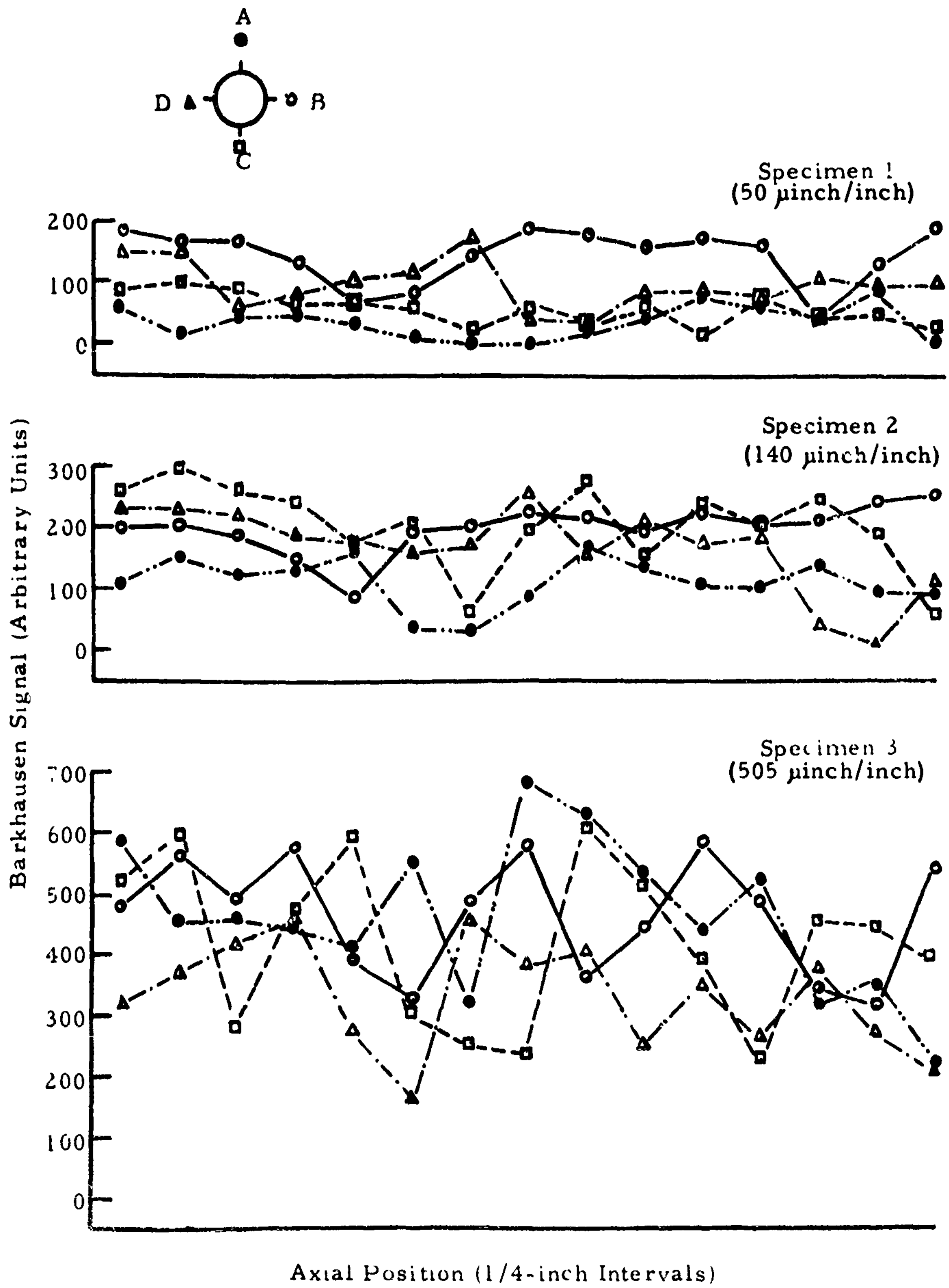

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FIGURE 6. BARKHAUSEN EFFECT MEASUREMENTS ON AUTOFRETTAGED AISI 4340 STEEL TUBES (TANGENTIAL ORIENTATION)

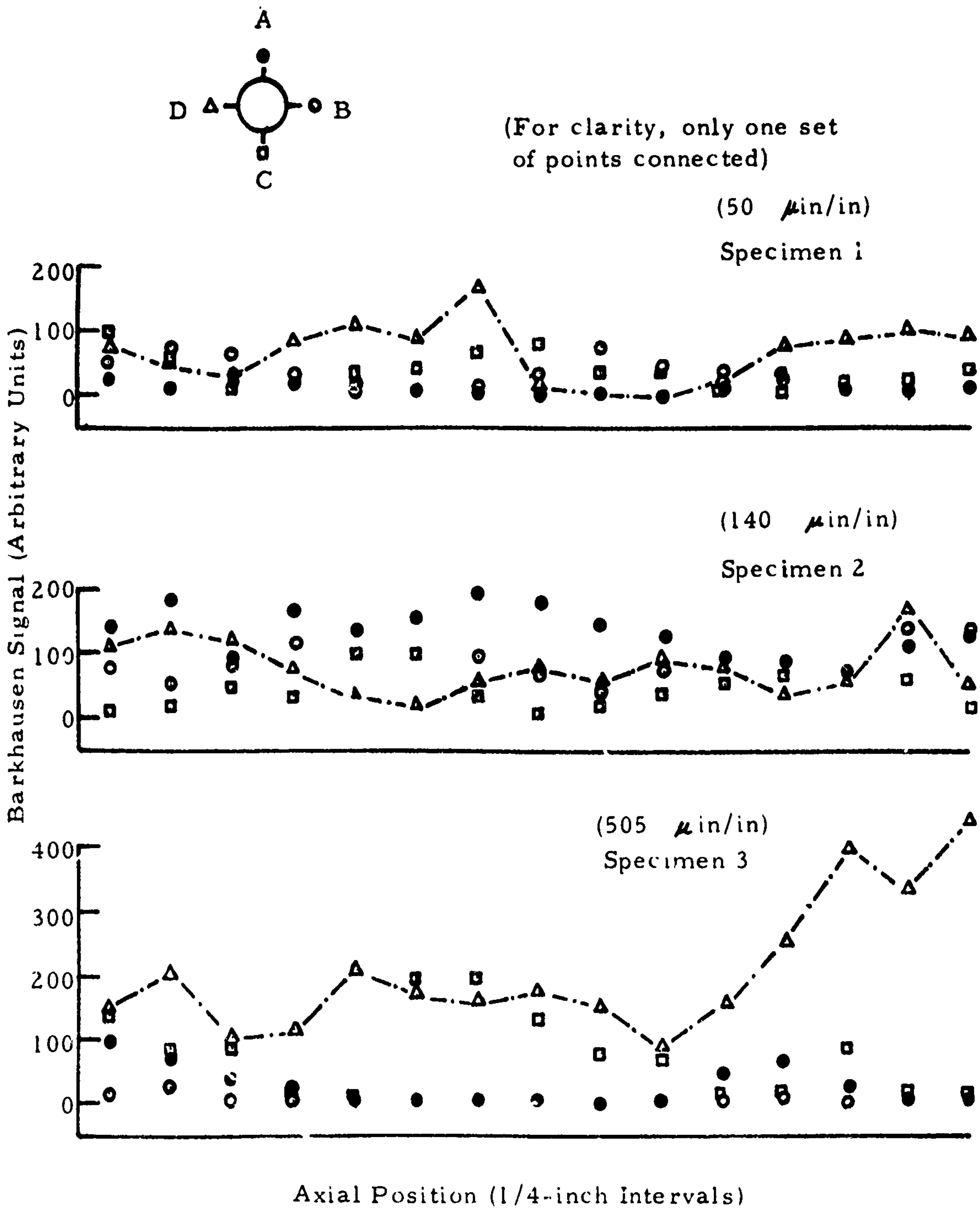

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FIGURE 7. BARKHAUSEN EFFECT MEASUREMENTS ON AUTOFRETTAGED AISI 4340 STEEL TUBES (LONGITUDINAL ORIENTATION)

the surfaces of the specimens were in the "as received" condition, it was considered possible that the observed variability might be due to purely superficial features such as tool marks, roughness, etc. To test this idea, a few mils of material were removed from the outer surface of specimen No. 2 by electropolishing, the reference grid accurately restored by using permanent fiducial marks, and the Barkhausen effect readings remade. The results obtained were substantially the same as those obtained before electropolishing. It was therefore concluded that the observed variability was not due to superficial effects. The observed variability must therefore reflect a true inhomogeneity in either the distribution of surface stresses induced by the autofrettage process, or in the magnetic properties of the material, or in both.

The following general conclusions are drawn from the foregoing experimental results:

(1) for each specimen the residual longitudinal stress is generally small compared to the tangential stress, but is not negligible;

(2) although there is substantial overlap in the tangential readings from specimen to specimen, there is a pronounced trend toward higher readings with increased tension, which readily separates the specimens and orders them in terms of increasing degree of autofrettage.

The latter result is made clear by averaging the four readings made at separate locations around each tube, but at the same location along the length of the tube. The result of this averaging is shown graphically in Figure 8

The "Boring Out" Experiment

Longitudinal and transverse strain gauges were bonded to Specimen No. 3 at midlength; these sets of gauges were applied, at 0°, 90° and 270°; one 90° quadrant was left open to accommodate the magnetic yoke and probe for making Barkhausen effect readings. An accurate reference grid for repositioning the probe was also applied to the outer surface of the tube. A lathe was equipped with a specially made face-plate adapter, a three-point steady rest, and a stiff boring bar. The inner bore was enlarged in successive stages. At the completion of each stage the tube was removed, the strain gauges read, and transverse Barkhausen effect readings made.

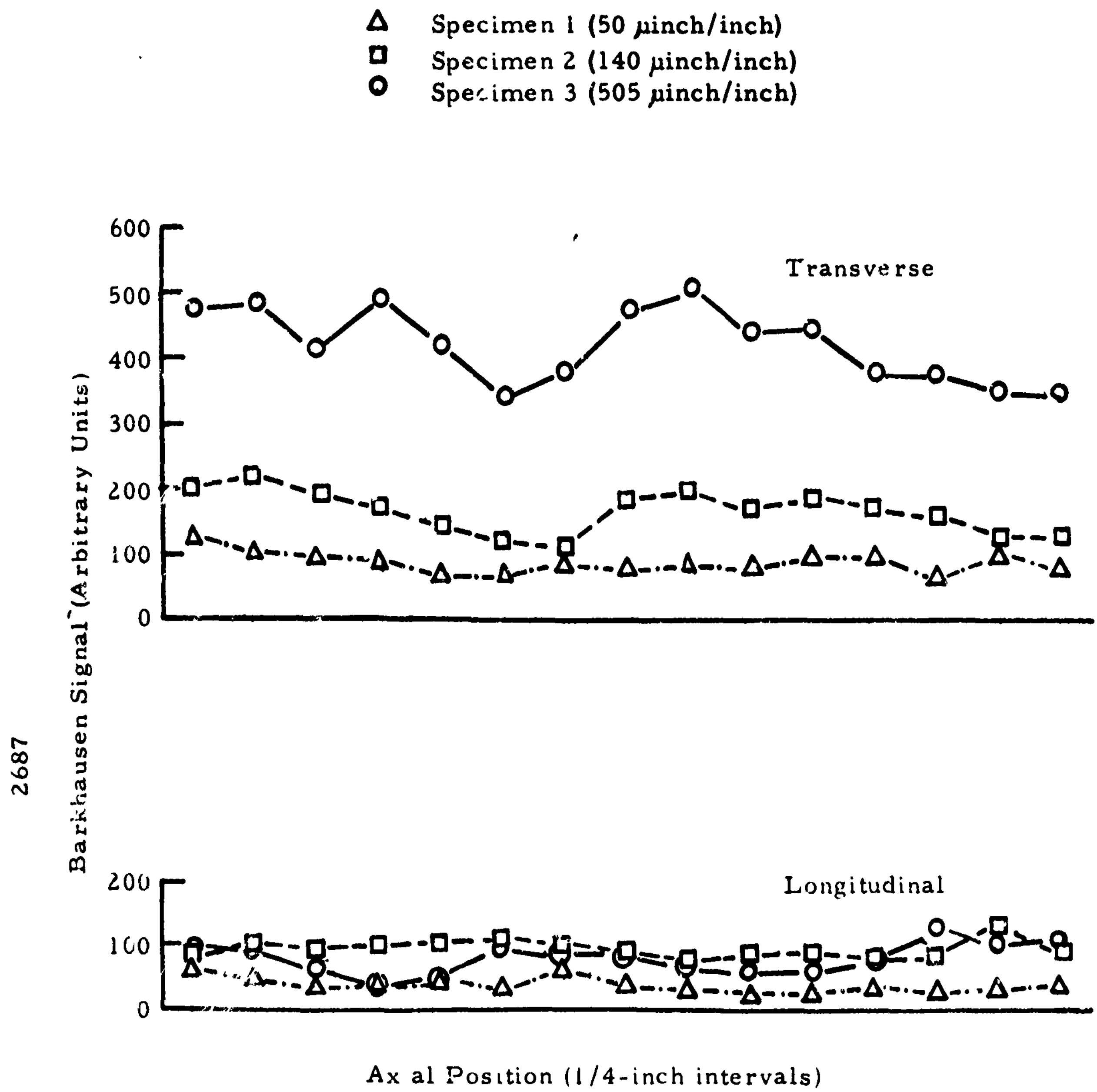

FIGURE 8. AVERAGE BARKHAUSEN EFFECT MEASUREMENTS ON AUTOFRETTAGED AISI 4340 STEEL TUBES

The original machining scheduled called for individual cuts of 0.005-inch depth. Excessive cutter wear was encountered, and it proved necessary to increase the depth of each cut to a minimum of 0.010 inch. A total of 20 machining stages were completed, which enlarged the bore diameter from 1-inch to 1.87 inches. Because of machining difficulties it proved to be impossible, within the scope of time and funding of the project, to continue the boring out operation to the point where the stress in the outer surface of the specimen tube was completely relaxed.

The Barkhausen reading results obtained at a representative position at the midpoint on the tube are shown graphically in Figure 9. Comparable results were obtained at other positions with due allowance for the point-to-point variability previously noted.

According to the report of Davidson <u>et al.</u>, (Reference 2) the original distribution of tangential stress along a radial line through the tube can, within a certain approximation, be obtained from a graph of a certain tangential strain function, plotted as a function of the bore radius as it is progressively enlarged in the boring-out operation. The required tangential strain function is, by definition:

$$F(r) = E'\Theta \left(\frac{b^2 - r^2}{2r}\right)$$

$$E' = \frac{E}{1 - \mu^2}$$

E = Young's modulus of elasticity (assumed to be 29×10^6 psi)

μ = Poisson's ratio (assumed to be 0.3)

$\Theta = \xi_t + \mu \xi_l$

ξ_t = tangential strain (inches/inch)

ξ_l = longitudinal strain (inches/inch)

b = outer radius of the tube (inches)

a = inner radius of the tube (inches)

r = variable radius (inches); $a \leq r \leq b$

Figure 10 is a graph of this tangential strain function as obtained from the strain data for Specimen 3. According to Reference 2, the slope of this curve gives the tangential stress directly; the result is shown in Figure 11. The indicated original value of the surface tensile stress ($\simeq$ 21 ksi) was

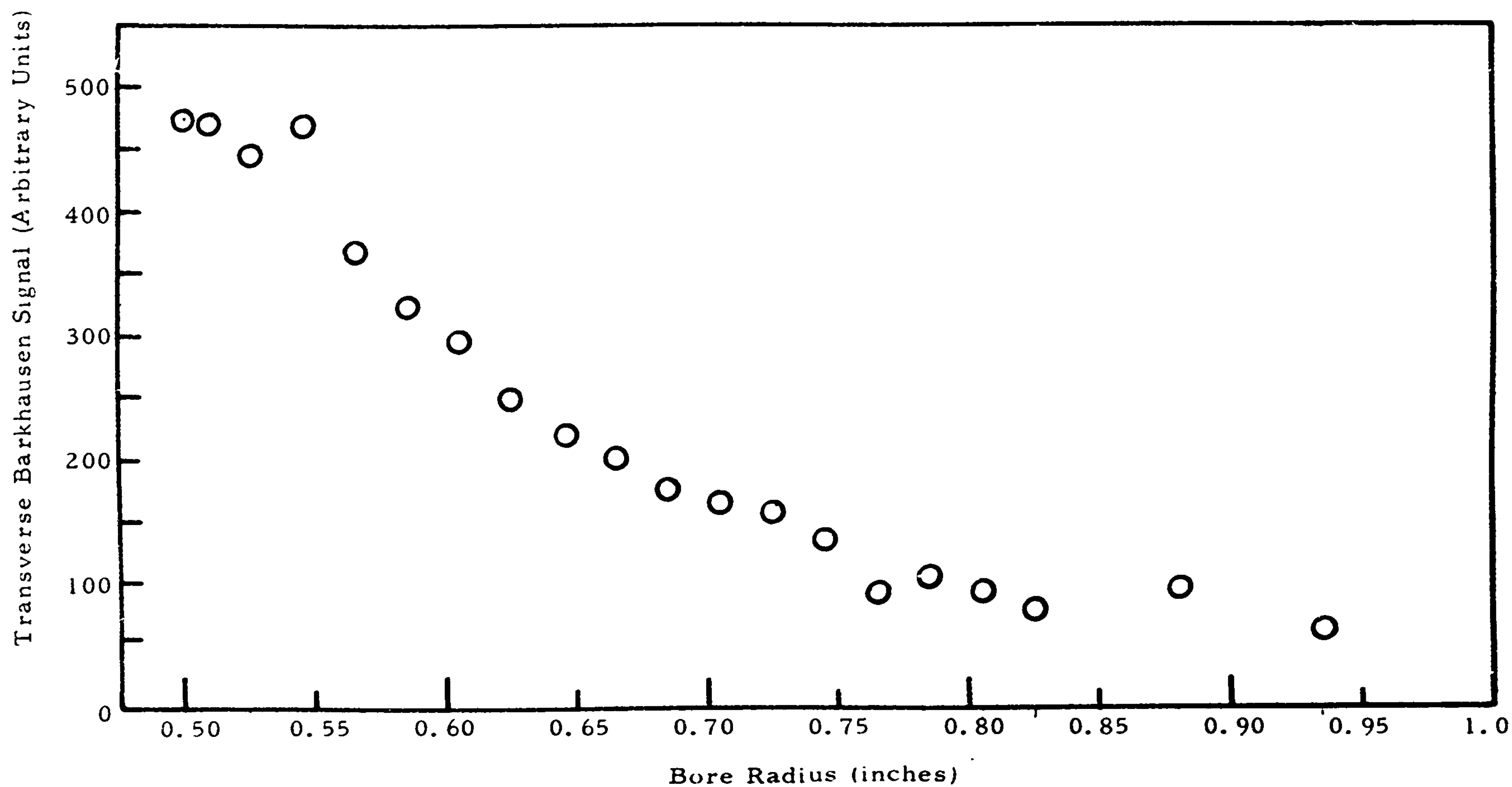

FIGURE 9. BARKHAUSEN EFFECT READINGS AS A FUNCTION OF BORE RADIUS, INDICATING RELAXATION OF SURFACE TENSILE STRESS.

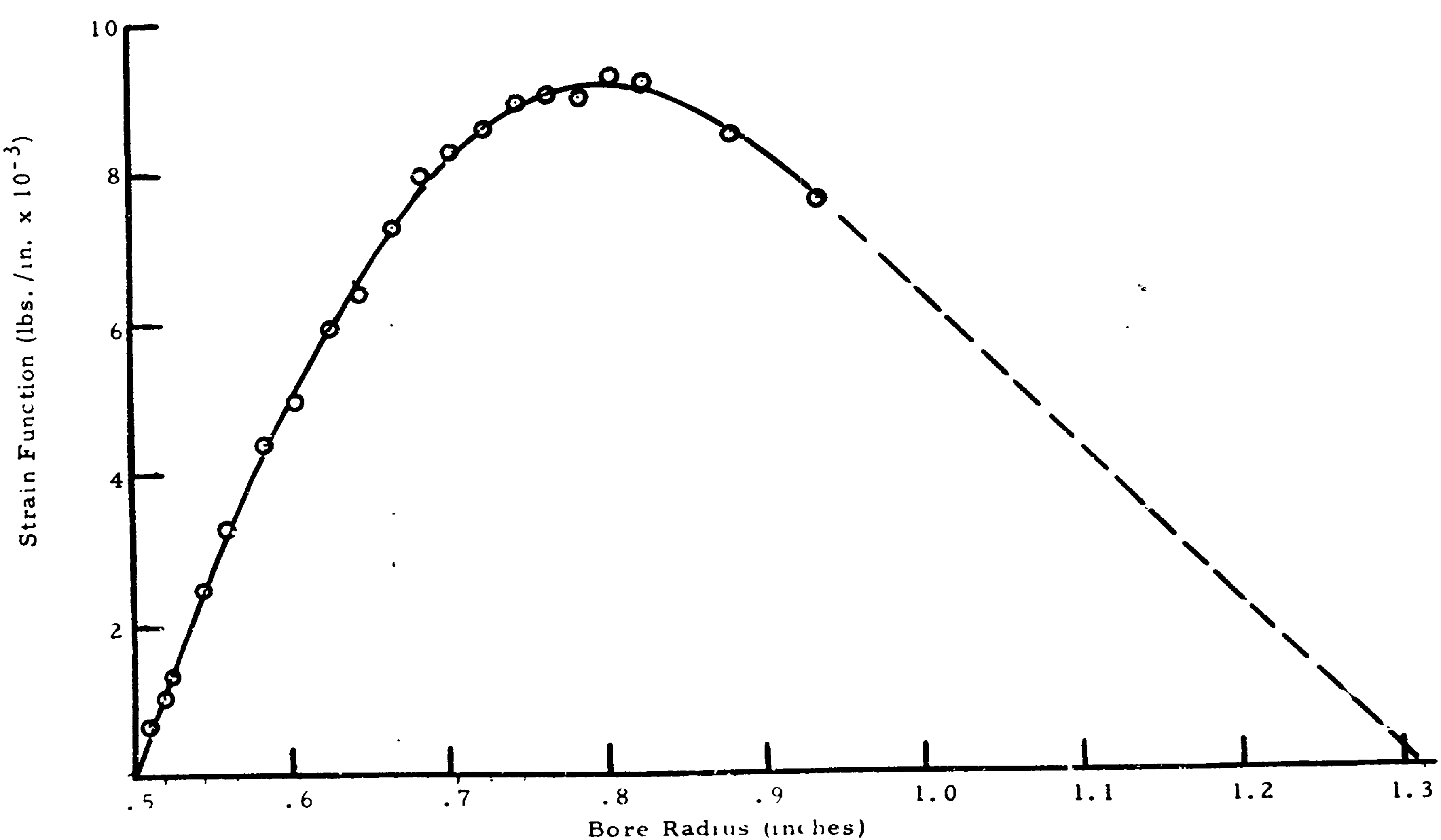

FIGURE 10. EXPERIMENTAL VALUES OF TANGENTIAL STRAIN FUNCTION VERSUS BORE RADIUS.

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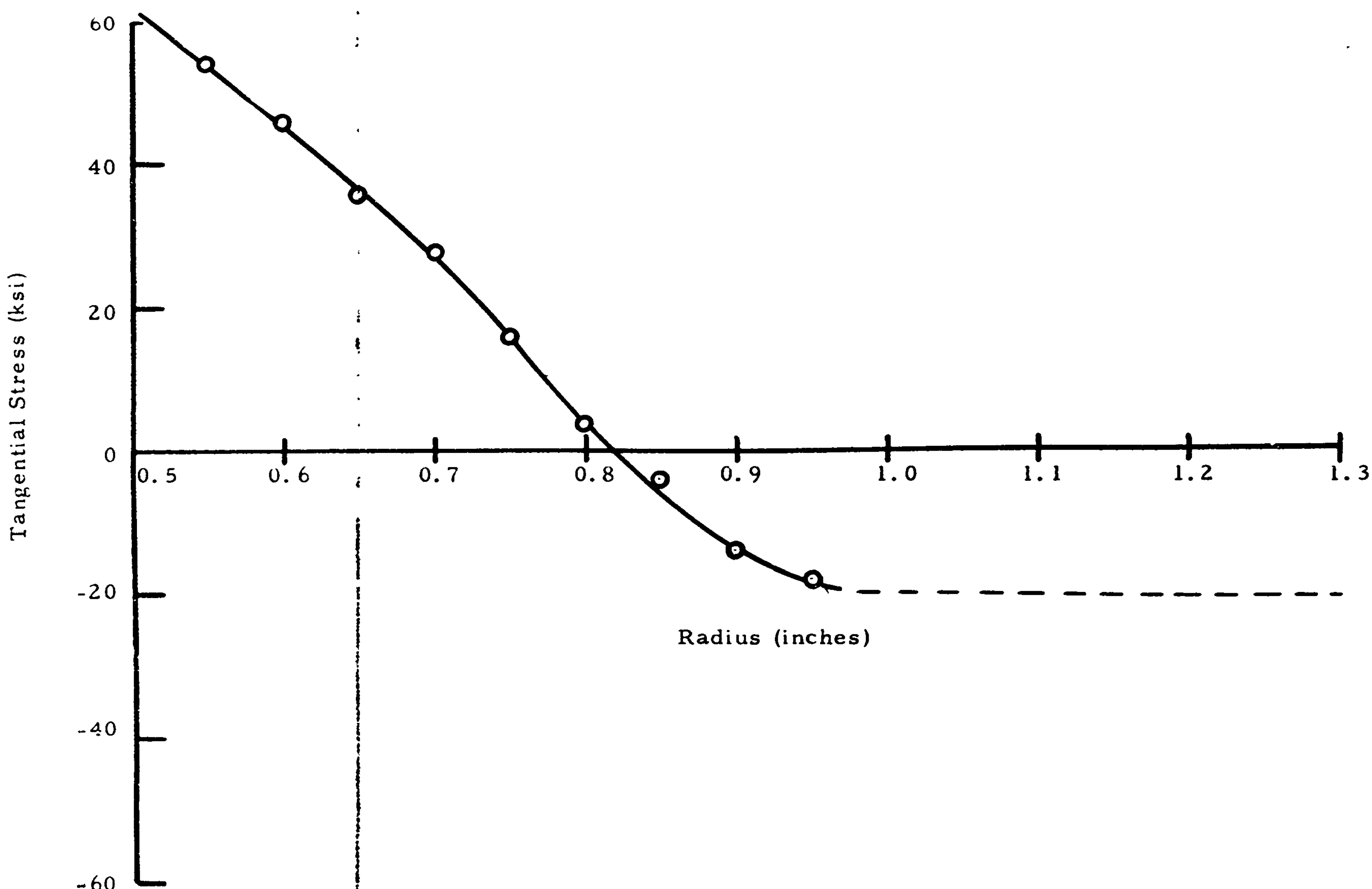

FIGURE 1. TANGENTIAL COMPONENT OF RESIDUAL STRESS IN AUTOFRETTAGED AISI 4340 TUBE

obtained by extrapolating the actual data to a radius corresponding to the surface of the specimen tube; this is in rough agreement with the value 15 ksi obtained by multiplying the measured residual surface tangential strain (505 μ inches/inch) by the assumed value of Young's modulus (29×10^6 psi).

EXPERIMENTS ON GUN TUBES

The laboratory Barkhausen effect stress measuring instrumentation was transported to Watervliet Arsenal for experiments on actual gun tubes. The first experiment consisted of making comparative Barkhausen effect measurements on a 175 mm M113E1 tube before and after it was autofrettaged. At this stage the outer surface of the tube has the (final) rough turned machined finish; the bore is uniform and has a smooth ground finish. Only the first third of the tube is autofrettaged, which includes the chamber and about 85 inches of the rifling. This is accomplished by lowering the tube, breech first, over a vertical mandrel with seals at each end of the mandrel, and hydraulically pressurizing the region between the mandrel and the tube. The overstrained region extends approximately from 10 inches to 150 inches from the breech. The nominal compressive stress at the bore resulting from overstraining is 90-100 ksi.

Special pole tips for the magnetic yoke used with the Barkhausen effect probe were used; one set was made to fit the bore surface in the tangential sense; the other set had flat tips and was used in making both longitudinal and tangential measurements at points on the outer surface; no longitudinal measurements were made inside the bore. Fiducial marks were located on the tube using fine lines inscribed in machinist's layout ink. The probe was positioned by hand as accurately as possible with respect to these fiducial marks using a steel ruler.

Although the Barkhausen readings made were not strongly sensitive to minor inaccuracies in position, some sensitivity was noted, particularly on the coarsely machined outer surface of the tube; this was probably due primarily to differences in lift-off of the magnetic yoke pole tips, as well as the sensory coil itself. In addition, localized variations in the effects induced by machining undoubtedly contributed to variability of readings with position. Where such effects were apparent, a group of measurements were made with minor repositioning of the probe assembly between measurements, and an average of these results tabulated.

Measurements were made in both the breech and muzzle regions of the tube, on both the bore and outer surfaces. In addition, measurements on the outer surface were made near the midpoint of the tube. Measurements inside the bore were limited to positions which could be reached by hand, i.e., about 28 inches from the breech. On both the bore and outer surfaces, detailed measurements were made only at positions along a straight line parallel to the tube axis, and in a vertical plane (the tube itself being horizontal). Photographs of the experimental arrangement are shown in Figure 12.

The results obtained are presented in Table I. The most crucial results are the readings obtained in the bore at the breech end of the tube, before and after autofrettaging. One notes that the readings obtained after autofrettaging are greater than the corresponding readings before autofrettaging by about a factor of four. Elsewhere on the tube, both in the bore and at the outer surface, the corresponding "before" and "after" readings are not significantly different.

The pronounced increase in the value of the readings in the autofrettaged region of the bore is quite unexpected. Careful and thorough checks were made to insure that the instrumentation was functioning normally; the anomolous result was therefore quite genuine. All previous experience with the Barkhausen instrumentation applied to high-strength steels has shown that material in compression gives lower readings than the same material in a substantially unstressed condition, whereas material in tension gives higher readings than does unstressed material. Why then this anomolous result? The most natural assumption is that the heavy plastic deformation undergone by the material near the bore surface modifies the magnetic properties of the material to such an extent that a stronger Barkhausen signal is obtained despite the high residual compressive stress at the bore surface. If this were true it would be expected that upon boring out the chamber (thereby removing the most heavily cold worked material) the effect of the residual compression (relaxed to a certain degree by the removal of material) would manifest itself in the normal manner, i.e., by substantially reducing the strength of the Barkhausen effect; as will shortly be demonstrated, such an effect was in fact observed. Unfortunately for the foregoing hypothesis, there is very little data available on the specific effects of plastic deformation upon the Barkhausen effect in complex alloy steels, and such data as does exist indicates that plastic deformation tends to reduce rather than increase the Barkhausen effect in such steels; nevertheless, this hypothesis should certainly be difinitively tested in future work. Another hypothetical explanation of the anomalous observation is that the immediate surface of the bore, in the region accessible to measurement, is affected by the autofrettage process in some manner other than simply overstraining it and leaving it in compression. For example, the seal between the mandrel and the bore is located in the region in which readings were made; although it seems implausible, the seals may have produced some effect.

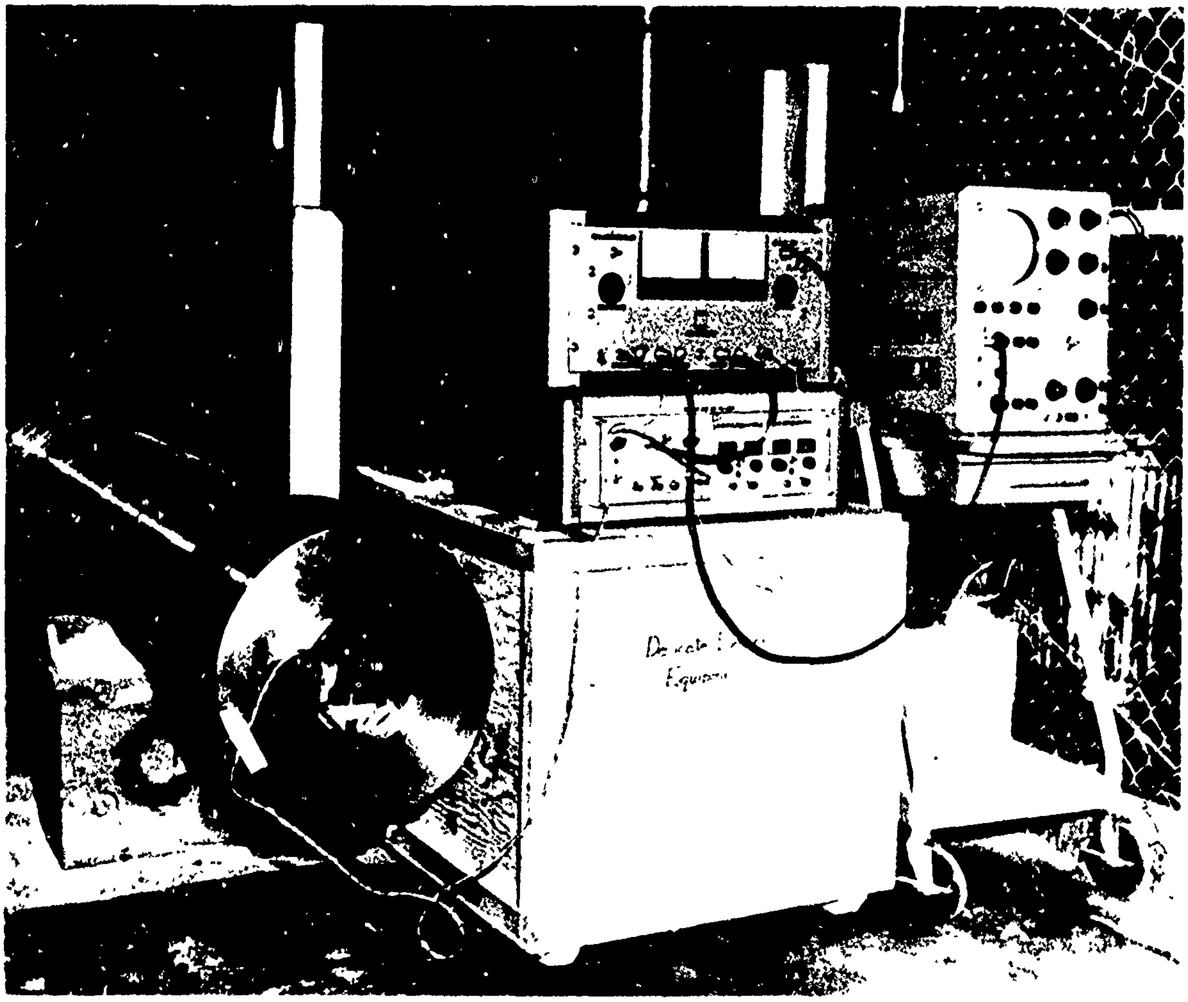

FIGURE 12. PHOTOGRAPH OF EXPERIMENTAL ARRANGEMENT FOR MAKING BARKHAUSEN EFFECT MEASUREMENTS ON A 175 mm GUN TUBE. Probe shown in position for tangential reading on bore surface. (U. S. Army Photograph)

A. Measurements Made on Bore Surface

Breech Region:

Position (inches from breech end)		12-7/8	17-1/8	18	19-13/16	20-3/4	25-7/8
Tangential reading	Before	44	12	20	66	32	86
	After	180	96	160	240	196	260

Muzzle Region:

Position (inches from muzzle end)		2-7/16	4-5/16	6-1/16
Tangential reading	Before	44	32	40
	After	80	28	56

B. Measurements Made on Outer Surface

Breech Region:

Position (inches from breech end.)		0.5	1.5	2.5	3.5	4.5
Tangential reading	Before	800	500	470	430	520
	After	900	420	540	560	660
Longitudinal reading	Before	232	78	12	0	0
	After	260	168	88	20	4

Muzzle Region:

Position (inches from muzzle end.)		2-7/16	4-5/16	6-6/16
Tangential reading	Before	90	210	1000
	After	110	250	1000
Longitudinal reading	Before	200	240	20
	After	54	264	20

Mid-point:

Position (inches with respect to fiducial mark).		2	4	6
Tangential reading	Before	600	680	680
	After	550	720	760
Longitudinal reading	Before	168	1	30
	After	196	2	38

TABLE I. BARKHAUSEN EFFECT READINGS ON 175 mm GUN TUBE BEFORE AND AFTER AUTOFRETTAGE.

Experiments on Other Gun Tubes

The scope of this project did not permit a repetition of the previously described experiment, as another tube was not immediately ready for autofrettaging. However, there were available some additional autofrettaged 175 mm tubes of which the chambers had been bored out and ground to final dimensions, and the barrel rifled. In addition, two finished 8-inch howitzer tubes were available; these tubes are manufactured in essential respects like the 175 mm tubes, except for the omission of autofrettaging.

The significant results obtained on the finished 175 mm tubes are presented in Table II. There are three striking features of the data: (1) the results were closely comparable for all three tubes; (2) the Barkhausen effect readings in the chamber region decrease progressively with distance from the breech; (3) the magnitude of the chamber readings near the breech was essentially that of unstressed material, while those away from the breech are very small, as would be expected of material in severe compression. Thus the results are precisely what previous experience with the Barkhausen effect instrumentation leads one to expect.

With the previously described anomalous results on the unfinished 175 mm tube in mind, it was thought that perhaps the indications of compressive stress in the chambers of the finished tubes might be solely due to superficial compression introduced by the chamber enlargement and finishing machining operations. To check this possibility, measurements were made in the chambers of two nominally identical 8-inch howitzers. As previously mentioned, these gun tubes are made of the same material and by the same general machining operations as is the 175 mm tube, the major difference being that the 8-inch tubes are not autofrettaged. The results of these measurements are presented in Table III. It is apparent therefrom that (1) the readings are comparable to those obtained in the substantially unstrained region near the breech in the chamber of the 175 mm tubes; and (2) no significant reduction in readings is obtained at successively greater distances from the breech in the 8-inch tubes. Thus it is concluded that the observed low readings in the finished chambers of the 175 mm tubes are not due solely to superficial finishing effects, and do reflect the compressive stress resulting from the autofrettage process.

Tube A:

Position (inches from breech).	1-1/2	2-1/2	3-1/2	4-1/2	6	8	28
Tangential reading, bore surface.	120	66	48	38	18	1	0
Average Tangential Reading on Outer Surface: 156							

Tube B:

Position (inches from breech)	1-1/2	2-1/2	3-1/2	4-1/2	5-1/2	6-1/2	12-1/2	25	40
Tangential reading, bore surface.	68	8	8	5	5	6	10	0	0
Average Tangential Reading on Outer Surface: 272									

Tube C:

Position (inches from breech)	1-1/2	2-1/2	3-1/2	5-1/2	12	24
Tangential reading, bore surface.	248	64	4	1	2	0
Average Tangential Reading on Outer Surface: 169						

TABLE II. BARKHAUSEN EFFECT READINGS ON THREE FINISHED AUTOFRETTAGED 175 mm GUN TUBES.

Tube A:

Position (inches from breech).	12	24
Tangential reading, bore surface	148	84
Average Tangential Reading Outer Surface: 57		

Tube B:

Position (inches from breech).	12	24
Tangential Reading, bore surface	192	176
Average Tangential Reading Outer Surface: 192		

TABLE III. BARKHAUSEN READINGS ON TWO 8-inch HOWITZER TUBES (NOT AUTOFRETTAGED).

CONCLUSIONS AND RECOMMENDATIONS

The results of the experiments performed on small scale autofrettaged tubes establish that the Barkhausen effect stress measuring instrumentation is proportionately sensitive to residual stress induced by mechanical overstraining, and that with appropriate calibration such instrumentation could quantitatively measure such stress over a useful range.

The results of the measurements made on a 175 mm gun tube before and after autofrettaging were not in agreement with previous results on similar material known to be in a state of high compressive stress. No firm explanation of this anomalous result can be offered at present, and further investigation is indicated.

The results obtained on finished autofrettaged 175 mm tubes and unautofrettaged 8-inch tubes indicate that the presence of high residual compressive stress induced by autofrettaging in the chamber of finished 175 mm tubes can be detected with the Barkhausen effect instrumentation, and that the influence of the stress induced by autofrettage is not seriously masked by superficial stresses induced by machining and finishing operations. Based on these results, it is concluded that the Barkhausen effect instrumentation could be used as a nondestructive means of distinguishing between finished tubes that have been autofrettaged, and those which have not.

The following recommendations are made:

1. The experiment in which Barkhausen effect measurements were made in the chamber region of a 175 mm gun tube before and after autofrettaging, and which yielded apparently anomalous results, should be repeated. Provision should be made for precise and reproducible positioning of the probe at any point within the bore; this will require special fixturing and a sufficiently long probe cable. The experiment should be extended to include bore measurements at all stages of chamber enlargement and finishing subsequent to autofrettaging.

2. With respect to the Barkhausen effect, further basic studies on the relative effects of plastic deformation and macroscopic residual stress in complex high-strength steel alloys should be conducted.

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