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BARKHAUSEN NOISE ANALYSIS AND FERROMAGNETIC MATERIALS

DOUGLAS J. STRAND
MATERIEL DURABILITY BRANCH

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ABSTRACT

At its foundations (ferromagnetic domains), the Barkhausen effect has a rich theory. An introduction to this theory is first given. The Barkhausen effect is defined and a description of how it comes about is given. Barkhausen Noise Analysis (BNA) is used as a nondestructive evaluation method. Completed applications of this are cited and explained. BNA is applicable only to ferromagnetic materials, so its use has primarily focused on armor applications in this study. The parameters which affect the method were also sought and the results given.

CONTENTS

INTRODUCTION

The Barkhausen effect is the result of the motions of ferromagnetic domains and domain walls called Block walls. The mechanics of how these walls are formed and how they adjust is based on the fact that everything tends to its lowest energy state. There are four energies involved in the process:

- Exchange energy,
- Magnetostatic energy,
- Anisotropic energy, and
- Magnetostrictive energy.

A theoretical examination of the Barkhausen effect is replete with these four terms, therefore, they are defined as follows:

Definition 1: Exchange energy is the energy due to the interaction of two spin states.

Definition 2: Magnetostatic energy is the energy of the magnetic field of a magnet; i.e., the energy associated with a permanent magnet.

Definition 3: Anisotropic energy is the excess energy required to magnetize a crystal in a hard, as compared to an easy, direction.

Definition 4: Magnetostrictive energy is the energy created by a strain on the material.[1]

Domain motion is governed by the struggle to minimize these four energies. Below is a list of the conditions under which the four energies are minimized.

Exchange energy: When all atomic dipole moments are parallel, this energy is minimized.

Magnetostatic energy: When the integral of $1/2\mu H^2$ overall space is minimized, this energy is minimized. H is the external field produced by the magnetic material.

Anisotropic energy: This is minimized when the magnetization is along an easy direction.

Magnetostrictive energy: When the material is oriented in such a way that changes in its dimensions are along the magnetization axis, this energy is minimized.[2]

An applied magnetic field will upset the minimizing balance of these four fundamental energies. The Barkhausen effect occurs during the process of restoring this balance.

THEORY

Destructive testing has the disadvantage of only allowing a very small portion of a lot of material to be inspected. With nondestructive evaluation, 100% of the samples can be tested without damaging even one specimen.

1. PLONUS, M. A. Applied Electromagnetics. McGraw-Hill, Inc., New York, 1978, p. 361-367.
2. Ibid., p. 361.

The major nondestructive testing techniques utilized by the Department of the Army at the U.S. Army Materials Technology Laboratory (MTL) and in the field are acoustic emission, electromagnetic, liquid penetrant, magnetic particle, radiography, and ultrasonic. The Barkhausen effect is an electromagnetic technique.

In its simplest form, the Barkhausen effect states that the hysteresis loop of a ferromagnetic material is not a smooth curve. There are discontinuities, or jumps, that occur along its path on a microscopic level.

Hysteresis results from the fact that the domain boundaries do not return exactly to their original positions upon removal of the external field $\vec{B}_0$.[3] It is illustrated by a graph of magnetic induction or flux density, B, versus applied field (intensity), H. The magnetic induction, $\vec{B}$, is the vector sum of the magnetic state of the material, $\vec{J}$, and the applied field, $\vec{H}$.

$$\vec{B} = \vec{H} + 4\pi \vec{J}$$ [4]

This discontinuous change in magnetization produces a noise-like signal similar to the time derivative of the actual magnetic flux into a coil which has been placed near to the material being magnetized.[5]

When the applied magnetic field strength exceeds certain threshold values, the domain walls inside the material will move, causing the Barkhausen jumps. Since the middle range of the magnetizing field, H, causes the steepest slope, $\frac{dB}{dH}$, in the hysteresis loop, it is here that these threshold values are most likely to be exceeded and Barkhausen jumps occur.[6] Irreversible domain wall boundary motions predominate in the medium field range.

At low field values magnetization increases by reversible boundary displacements, and in the high field range reversible domain rotations predominate.[7] The reason that the phenomenon at mid-range is irreversible while at low, and at high range it is reversible, is that the potential barriers caused by dislocations, precipitates, or other obstacles which "pin" the walls are surmounted at mid-range due to the greater change in flux density here.[8]

Microscopically, the domain wall movements are caused by changes in direction of atomic magnetic moments. These moments change their directions by 90 or 180 degrees inside domain walls at the so-called easy magnetization directions. However, no such changes occur until wall displacements are completed.[9] For materials such as iron, the <100> lattice directions are the easy directions.[10]

Domain walls move through a crystal when an applied magnetic field is varied. If the domain wall encounters an inclusion, it is elastically jerked onto it and will stay on top of the

3. HALLIDAY, D., and RESNICK, R. Fundamentals of Physics. John Wiley and Sons, Inc., New York, 1970, p. 621.
4. LEEP, R. W. *The Barkhausen Effect and its Application in Nondestructive Testing* in Physics and Nondestructive Testing. W. J. McGonnagle, ed., Gordon and Breach, Science Publishers, Inc., New York, 1967, p. 440.
5. SUNDSTROM, O., and TORRONEN, K. *Materials Evaluation.* v. 37, February 1979, p. 51.
6. WEINSTOCK, H., ERBER, T., and NISENOFF, M. *Phys. Rev. B.* v. 31, 1985, p. 1535.
7. LEEP, R. W. *Op. Cit.* p. 440-441.
8. WEINSTOCK, H. *Op. Cit.* p. 1536.
9. BROWN, W. F., Jr. Magnetostatic Principles in Ferromagnetism. Interscience Publishers, Inc., New York, 1962, p. 167.
10. SUNDSTROM, O., and TORRONEN, K. *Op. Cit.* p. 51.

inclusion until the magnetic field is further varied; then it will move away from the inclusion elastically until it reaches an "elastic limit" where it will snap free from the inclusion.

These jerks and snaps are what cause an induced voltage pulse in a coil wound on the specimen.[11]

Two important formulas arise from the domain wall calculations.[12] First, a formula for the effective wall thickness:

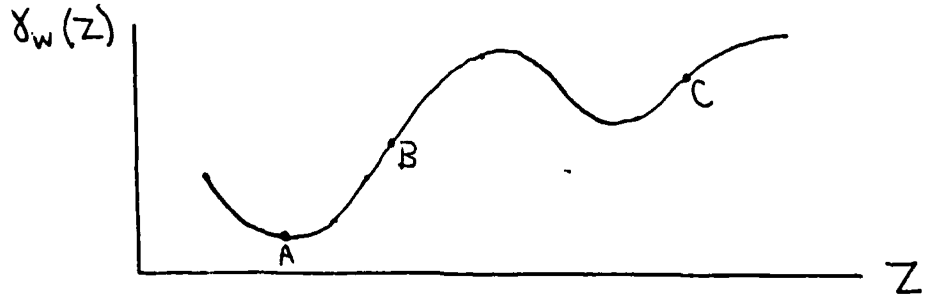
$$\delta = 2\sqrt{\frac{C}{2K_o}} = \frac{\sqrt{2C}}{K_o}$$

where C is the particle mass and K_o comes from the crystalline-anisotropy energy density, $K_o \alpha_1{}^2$. Secondly, a formula for the free energy γ_w per unit area of the wall:

$$\gamma_w = f_H = 2K_o \int_{-\infty}^{+\infty} \cos^2 \phi \; dZ = \sqrt{2CK_o} \int_{-\frac{\pi}{2}}^{+\pi/2} \cos \phi \; d\phi = 2\sqrt{2CK_o}$$

where ϕ is the meridional angle of cylindrical coordinates. ϕ is the angle that the magnetic moment makes with an arbitrary initial or standard direction.[13]

There are two pressures on the domain wall which must balance in order for it to be in equilibrium. The first is the pressure due to the magnetic field, and the second is the pressure due to inhomogeneities, $-\frac{d\gamma_w(Z)}{dZ}$, where $\gamma_\omega(Z)$ is the energy per unit area of a wall "at" (i.e., with its midplane at) Z. Thus, $\gamma_w(Z)$ will be at a minimum, A, at zero field. As the field increases, the wall moves reversibly until it reaches a point of inflection, B, of $\gamma_w(Z)$. From here it goes to a position of stable equilibrium, C, by undergoing a finite irreversible displacement. This is a Barkhausen jump.[14]



APPLICATIONS

The Barkhausen effect can determine three things:

1. Stresses in technical ferromagnetic materials.

2. Surface grain size.

11. PASLEY, R. L. *Materials Evaluation*. v. 28, July 1970, p. 158.
12. BROWN, W. F., Jr. *Op. Cit.* p. 158.
13. Ibid., p. 150.
14. Ibid., p. 165.

3. Different types of heat treatment.[15]

The reason that the Barkhausen effect is important to NDE is that a Barkhausen signal response is an indication of stress in a material. It is directly proportional to the stress that is present. Thus, this paper will deal with number one above; numbers two and three are dealt with only in the respect that the theory discussed applies to them also.

Barkhausen noise is proportional to stress because the number and amplitude of the oscillations in magnetization are altered by the local strain centers which impede the domain motion. Therefore, local variations in microstructure and dislocation density will alter the signal as well as stress, saturating the signal at approximately 100 kilopounds per square inch (ksi), tension, or compression. Despite these calibration obstacles, the technique is promising for field measurements on steels.[16]

In general, residual stress will be relieved by a tensile strain of order 2Y/E,[17] where E is Young's modulus and Y is yield strength. Yield strength is defined to be the stress required to produce some specified plastic deformation, usually of the order of a few tenths of a percent; i.e., below the yield strength the deformation is almost entirely elastic.[18]

Mathematically, $E \equiv \frac{\sigma}{\in}$, where σ is normal stress and $\in$ is longitudinal strain. σ and $\in$ are in the same direction. Completing the description of the variables:

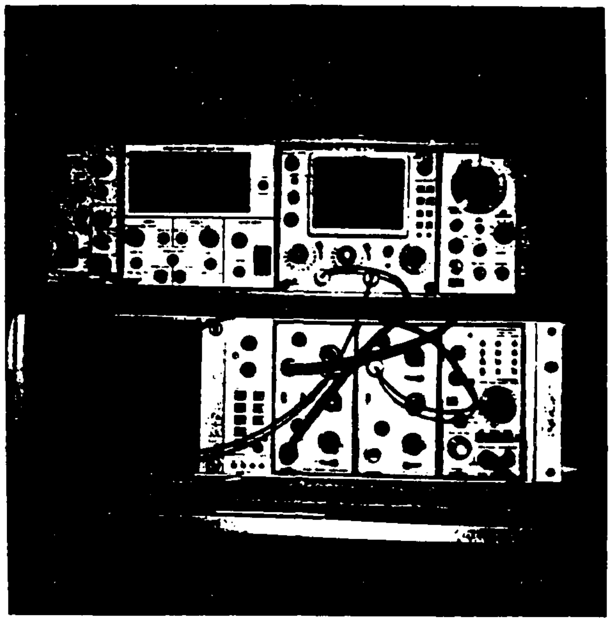
$$\sigma = \frac{F}{A},\ d\in = \frac{dl}{l},\ \text{and}\ \in = \int_{l_o}^{l_1} \frac{dl}{l} = \ln \frac{l_1}{l_o}.$$ [19]

The Barkhausen method is often called Barkhausen Noise Analysis (BNA) because it literally creates noise. There are several ways of analyzing this Barkhausen noise:

- Mean or maximum noise amplitude measurement,
- Spectral density measurement, and
- Determination of the pulse-height distribution profile of the noise.[20]

The instrumentation used at MTL is based on the third method of analysis, a picture of which is shown below:

15. WAFIK, A. H. *Journal of Magnetism and Magnetic Materials*. v. 42, 1984, p. 23.
16. NOYAN, I. C., and COHEN, J. B. *The Nature of Residual Stress and its Measurement* in Sagamore Army Materials Research Conference Proceedings No. 28. Plenum Press, New York, 1982, p. 9.
17. McCLINTOCK, F. A., and ARGON, A. S. Mechanical Behavior of Materials. Addison-Wesley Pub. Co., Reading, Massachusetts, 1966, p. 433.
18. GUY, A. G. Elements of Physical Metallurgy. Addison-Wesley Pub. Co., Reading, Massachusetts, 1959, p. 283.
19. MEYERS, M. A., and CHAWLA, K. K. Mechanical Metallurgy: Principles and Applications. Prentice Hall, Englewood Cliffs, New Jersey, 1984, p. 4-6.
20. SUNDSTROM, O., and TORRONEN, K. *Op. Cit.* p. 52.



AUTOFRETTAGED CANNON TUBE

The Barkhausen effect was used at MTL to examine a ring section from an eight-inch cannon tube that had been autofrettaged (prestressed beyond the yield strength). The ring section had a 17-inch outside diameter, 4.43-inch wall thickness, 8.14-inch bore diameter, and was approximately two inches thick. Autofrettage is a cold working process which produces a beneficial **compressive** residual hoop stress at the inside diameter of a cylinder and a resulting tensile residual hoop stress on the outside diameter. Strain gages were loaded to the ring section at several locations on its face and at the inside and outside diameters. Additional surface stresses were induced by grinding one face of the disc in a direction parallel to an arbitrarily selected zero degree position. In each of four quadrants, station numbers (measuring points) were located at 1/2-inch intervals in a radial direction. This arrangement is shown in Figure 1. The intent of the laboratory work was to relieve the residual hoop stresses and determine the magnitude of the previously existing hoop stresses by measuring the resulting strains. Therefore, after all the Barkhausen measurements were made, the disc was cut open radially.*

Measurements were taken at each station at $\theta = 180^\circ$ and 270° with probe orientations tangentially, radially, and at 45°, as shown in Figure 1. The hoop stress direction is the tangential direction. Even though all measurements were taken opposite from the side that the strain gages were on, measurements at the 0° and 90° radial lines were prevented by the strain gage leads. Table 1 shows the data collected.

Figure 2 shows oscilloscope records of selected measurements. A high tensile stress station was chosen along with a high compressive one for comparison. The waveform of the magnetizing current used for all measurements is shown. This figure shows that the Barkhausen response is over 30 times more sensitive to tension than it is to compression.

*HATCH, H. P. Nondestructive Evaluation Branch, U.S. Army Materials Technology Laboratory, Watertown, Massachusetts. Unpublished notes.

Table 1. MEASUREMENTS AT θ = 180° AND θ = 270°

Station No.	Tangential ATTN	Tangential Meter	Radial ATTN	Radial Meter	45° ATTN	45° Meter
			Measurements @ θ = 180°			
1	2	372	—	—	—	—
2	2	336	5	1105	5	544
3	2	423	5	617	5	364
4	5	290	5	484	5	375
5	10	388	5	470	5	478
6	10	781	5	490	5	728
7	10	936	5	517	5	862
8	10	980	5	587	5	923
9	10	1006	—	—	—	—
			Measurements @ θ = 270°			
1	2	533	—	—	—	—
2	2	461	5	746	5	390
3	2	354	5	351	5	270
4	5	271	5	271	5	321
5	10	483	2	429	5	529
6	10	889	2	401	5	743
7	10	1009	2	425	5	990*
8	10	983	2	467	5	784
9	10	1011	—	—	—	—

*Varied from 1000→950 with time. (Occurred only @ this particular location.) Radial & 45° measurements were not taken at station #'s 1 and 9 because probe pole pieces extended beyond ID & OD, respectively. Correct all meter readings for amplifier gain (ATTN) & amplifier background noise

Ampl. Gain = 1 @ ATTN Pos. 10

Ampl. Gain = 2 @ ATTN Pos. 5

Ampl. Gain = 5 @ ATTN Pos. 2

Background (Ampl.) Noise Meter Reading	@ Attenuation Position
065	10
096	5
199	2

For Correction: 1st Subtract Noise Value, Then Divide By Gain.

Figure 3 shows that the 45° probe orientation gives a stronger Barkhausen response for a station in high tension, while the radial orientation gives a stronger response for a station in high compression.

At the time that the Barkhausen measurements were made, strain gage measurements were taken for comparison at the bore and outside diameter. A measurement was also taken at the neutral stress position. Figure 5 shows a plot of residual stress versus station number based on these three data points while assuming a monotonic variation in residual hoop stress from inside diameter (ID) to outside diameter (OD).

Combining the data from Figures 4 and 5, a plot of **residual** stress (rather than applied stress) versus Barkhausen amplitude can be made for the first time, as shown in Figure 6.

In Figure 4, Barkhausen amplitude was plotted against station number at the 180° radial line for the tangential (hoop) stress. In Figure 7, the same plot was made for the radial and 45° probe orientations. Note the flip-flop from the inner diameter to the outer diameter. This means that there is more tension in the radial direction than in the 45° direction near the inner diameter, and the reverse near the outer diameter.

Combining Figures 5, 6, and 7, the plot in Figure 8 is obtained. Note that the residual stress varies over a much greater range in the tangential direction than in either the radial or 45° directions in this autofrettaged ring. There is much less residual stress in the radial and 45° directions. As would be expected, the 45° readings are about halfway between the radial and 90° (tangential) readings.*

SINGLE TOOTH BENDING FATIGUE TESTS

The Barkhausen method was used for single tooth bending fatigue tests. A gear fixture and a 4-square test pinion were used. The gear used was a 9310 carburized gear (#2PH-14) which had no prior testing history. The fixture was designed so that only every third tooth could be fatigued. A bushing had to be inserted in order to locate the gear on the fixture shaft. The splines on the inside diameter of the gear had to be removed in order to do this. Table 2 shows a significant decrease in the Barkhausen amplitude after the bushing was pressed in. This appears to be due to two facts; first, the pressure which the bushing exerts against the fixture, though small, offsets some of the residual stress in the fixture, and second, the substance of the bushing appears to attenuate the signal.

A fatigue test was done on root #1. The tooth failed at 5,100 cycles. It was determined that a significant overload had been applied inadvertently in the initial setup.

Table 3 shows the data collected from a second fatigue test done on root #4. This tooth failed at 108,700 cycles. These results tend to indicate that the BNA signal amplitude correlates in direct proportion to failure; i.e., the larger the BNA amplitude, the closer the gear is to failure. The data does show that this is not a 100% correlation; i.e., on a few rare occasions, the signal amplitude did go down after continued fatigue cycles. The bushing was removed and the remaining roots 7, 10, and 13 were rechecked.

There is an apparent **increase** in Barkhausen amplitude after removing the bushing because there was a decrease after it was installed.†

*HATCH, H. P. Nondestructive Evaluation Branch, U.S. Army Materials Technology Laboratory, Watertown, Massachusetts. Unpublished notes.
†Ibid.

Table 2. FATIGUE TEST RESULTS

	Root #	Sig. Ampl. (@ Pos. 0.05)
Gear 2PH #14 (9310) - Recheck Measurements After Boring Out Splines	1	277
	4	277
	7	278
	10	277
	13	285

		Sig. Ampl. @ Micrometer Pos.		
	Root #	0.25	0.50	0.75
Press in Bushing for Fatigue Fixture - Recheck Measurements	1	255	263	270
	4		257	
	7		268	
	10		277	
	13		262	

		Sig. Ampl. @		
	Root #	0.25	0.50	0.75
At 0 Cycles: Root #4	4	257	262	268
	7		268	
	10		273	
	13		263	
After 25,000 Cycles: Root #4	4	255	263	267
	7		271	
	10		271	
	13		264	

Table 3. FATIGUE TEST RESULTS

		Sig. Ampl. @		
	Root #	0.25	0.50	0.75
Continuing: After 50,000 Cycles: Root #4	4	256	263	268
	7		270	
	10		270	
	13		260	
After 100,000 Cycles: Root #4	4	255	262	268
	7		271	
	10		271	
	13		263	

	Root #	Sig. Ampl. @ 0.50	Demag.	Again
Tooth Failed @ 108,700 Cycles - Remove Bushing and Recheck Remaining Roots, 7, 10, 13	7	295	292	295
	10	286	282	284
	13	294	295	294-295
	14	292	300	294

	Root #	Sig. Ampl.
	1 (Root A)	277

ELECTRONICS

The flux density, B, during the magnetizing cycle was monitored to better understand the Barkhausen response. Therefore, a Hall Amplifier was designed for use with the available Bell, Inc. Hall Detector FH-301-040. In the AM 501, there is a voltage of +33.5 V which is unregulated. A constant 15 ma control current was established in the Hall Detector by adding a 12-volt, 3-terminal regulator, type 7812. The operating characteristics of this detector are listed in Table 4. Figure 9 is a schematic of this Hall Amplifier. A Tektronix AM 501 Operational Amplifier was used.*

Table 4. HALL DETECTOR

Hall Detector FH-301-040
$R_{in} = 60\ \Omega$
$R_{out} = 85\ \Omega$
Mag. Sens. V_B @ I_{cn} = 12 mv/KG
Prod. Sens. V_{IB} = 0.8 V/A·KG
Nominal I_{cn} = 15 ma (30 ma max.)
$V_H = V_{IB} (I_{cn})\ B$; for B = 1 KG
V_H = 0.8 V/A·KG x 0.015 A x 1 KG = 12 mv

PARAMETERS

After using the Barkhausen effect in these studies, it was observed that there are several parameters which may affect Barkhausen measurements. Some of the microstructural parameters which have been found to affect the Barkhausen response are grain size, texture, precipitation, pearlite morphology, deformation, and anisotropy.

Anisotropy in steels is of particular importance. BNA can be used to analyze the direction of easy magnetization; i.e., the <100> crystal direction. Several ways have been sought to correlate BNA response to the sheet anisotropy parameters, r and Δr.[21]

$$r \equiv \frac{\epsilon_p}{\epsilon_t}$$

where ϵ_p is the plastic strain in the direction of the plane of the sheet for a tensile specimen and ϵ_t is the strain in the direction of sheet thickness.

The **normal** anisotropy of a sheet is measured by r, while Δr measures the **planar** anisotropy of a sheet.

$$\Delta r = 1/2\ (r_0 - 2r_{45} + r_{90}),$$

where r_0, r_{45}, and r_{90} are values of r measured at the angles of 0, 45, and 90 degrees from the rolling direction. A stress-free specimen is necessary for the evaluation of anisotropy.[22]

*HATCH, H. P. Nondestructive Evaluation Branch, U.S. Army Materials Technology Laboratory, Watertown, Massachusetts. Unpublished notes.

21. SUNDSTROM, O., and TORRONEN, K. Op. Cit. p. 53.
22. SUNDSTROM, O., and TORRONEN, K. Ibid., p. 53.

The effect of a constant magnetizing rate at various current levels against a constant current amplitude at various magnetizing rates was examined, as shown in Figure 10. It is clearly evident from the graph on the right in Figure 11 that for a constant magnetizing rate (slope of magnetizing curve), the Barkhausen Amplitude is **independent** of magnetizing current amplitude (from 0.2 to 1.0 ampere) and frequency for a given thickness. Therefore, magnetizing rate is one parameter which should be maintained constant for comparative measurements.[23]

THICKNESS PARAMETER

A step block was fabricated from Hi-Hard steel to determine the effect of specimen thickness on the Barkhausen response. Measurements were taken with the Barkhausen probe parallel to (||) and perpendicular to (⊥) the longitudinal axis of the step block. The flat, or bottom, side of the above step block was ground in the longitudinal direction, and the stepped side was ground in the transverse direction. Figure 12 shows a picture of the block and the first set of data taken. Figures 13 and 14 show oscilloscope records of the data including the magnetizing current, the actual field, and the waveform of the envelope detected Barkhausen noise burst.

Significant differences are noted between || and ⊥ readings on each step. Differences are most likely the result of grinding induced stresses. Therefore, the block was thermally stress relieved and the measurements were repeated. It was stress relieved by tempering at 1100°F for one hour and furnace cooling to room temperature in five and one-half hours. Table 5 shows the Barkhausen measurements that were taken after this was done.

Table 5. STRESS RELIEVED STEP BLOCK

	Stress Relieved Step Block by Tempering @ 1100°F for 1 Hour & Furnace Cool to RT in 5-1/2 Hours							
					Corrected Readings			
	Step Side		Flat Side		Step Side		Flat Side	
Step Thick.	||	⊥	||	⊥	||	⊥	||	⊥
5/8"	444	370	700	370	182	145	310	145
1/2"	430	670	800	363	175	295	360	142
3/8"	492	520	924	432	206	220	422	176
1/4"	450	640	1050	440	185	280	485	180
1/8"	540	915	880	500	230	418	400	210
1/16"	625	870	1040	598	273	395	480	259

The Following in Chemical Analysis of High-Hard Tensile Bars and Above Step Block

C = 0.3	Ni = 0.002
Mn = 1.4	Cr = 0.038
Mo = 0.19	B = 0.005

23. HATCH, H. P. *Op. Cit.*

Figure 15 shows the final results.[24] After tempering, it is seen that the difference between the parallel orientation and the perpendicular orientation is less for the step side than for the flat side. It is seen that the Barkhausen amplitude, generally, decreases as the thickness increases. The data also clearly shows that the step side parallel orientation is almost the same as the flat side perpendicular orientation all along the specimen! There doesn't seem to be any reason why this should be true as the two sets of conditions are quite unrelated to each other; nevertheless, it is important to note this result.

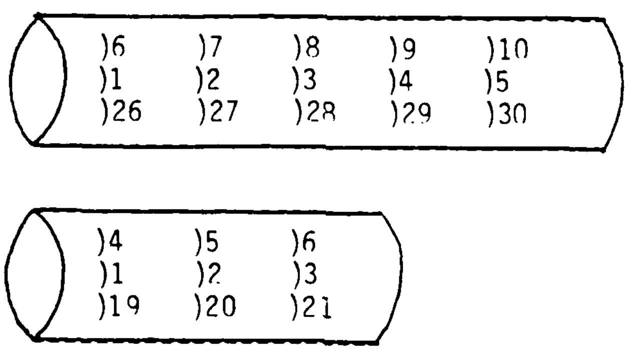
EFFECTS OF STRAIN

A pertinent study by A. H. Wafik at Ain-Shams University in Cairo, A.R. Egypt[25] shows that the Barkhausen response is affected by strain in different ways for different materials. Figure 16[26] shows that strain does **not** affect the Barkhausen response for fine wires of iron, but it **does** affect the response for fine wires of nickel and iron-nickel alloy. This is found by examining the width of the dispersal band of V_B, the potential difference of Barkhausen jumps with respect to strain using a constant magnetizing current. These results help determine if such wires would make good strain gages.

TOW MISSILE

The Barkhausen Noise Analysis method was used to examine residual stress in pieces of pipe from the U.S. Army's TOW Missile. This was done by The American Stress Technologies, Inc. in Bethal Park, Pennsylvania in conjunction with MTL. A Stresscan 500C was used with a miniature general purpose sensor #2224.

The outside diameters and inside diameters of the pipes were examined. A sketch of the positions examined is shown below:



Each position was tested in both the circumferential and transverse directions. Position #1 is marked as shown on each tube.

24. HATCH, H. P. *Op. Cit.*
25. WAFIK, A. H. *Op. Cit.* p. 23.
26. Ibid., p. 24.

Two conclusions can be drawn from this data. First, for all OD measurements, the circumferential measurements resulted in much higher values than the transverse measurements. Secondly, the reverse was found for all of the ID measurements; i.e., the transverse direction produced much higher values than the circumferential measurements.[*] The data is included in Figures 17 through 32.[†]

This data shows the precision, accuracy, and effectiveness of the BNA method for measuring residual stress in cylindrical objects of ferromagnetic materials.

CONCLUSIONS

The theory of the Barkhausen effect holds much promise for understanding of electromagnetic phenomena, far beyond its apparent original realm.

Regarding the autofrettaged cannon tube, the BNA method was able to find the residual stress at any point desired. The greatest change in stress was from the inside diameter, where there was a large compressive stress, to the outside diameter, where there was a large tensile stress.

From the data collected, it is concluded that the BNA method is a reliable way of determining when a gear tooth is about to fail from fatigue.

It is also concluded that there are many variables that affect the Barkhausen response, and by carefully controlling all but one of these variables, the effects can be determined. The effect of a constant magnetizing rate and of specimen thickness was examined. It was found that the Barkhausen amplitude is independent of magnetizing current, but it is indirectly proportional to the specimen thickness. The type of material examined will also affect the Barkhausen response to strain.

In final conclusion, it should be noted that every time the sophistication of electronic technology increases, the BNA method becomes more powerful and can be applied to a wider range of situations. This has been demonstrated in this paper by the fact that the final study was done by a more sophisticated device, the Stresscan 500C, than the initial studies.

ACKNOWLEDGMENTS

I would like to thank Harold Hatch (retired - 1985) of the U.S. Army Materials Technology Laboratory in Watertown, Massachusetts. Much of the data in the Applications Section of this paper are due to him. He worked patiently with me on these topics and I have attempted to carry on his work in nondestructive testing which I believe to be of an exceptional quality.

*EHRMAN, R. Report No. 175, American Stress Technologies, Inc., Bethel Park, Pennsylvania, 1988. Unpublished Research.
†Ibid.

I would also like to thank Robert Ehrman and Kirsti Tiitto of American Stress Technologies, Inc. in Bethel Park, Pennsylvania. They performed some excellent tests on some of our specimens with a new technology which we feel has a very bright future.

Finally, I wish to thank Linda Chin for a superb job with the stenography of this paper. Her efforts and skills were an integral part of this paper and are greatly appreciated.

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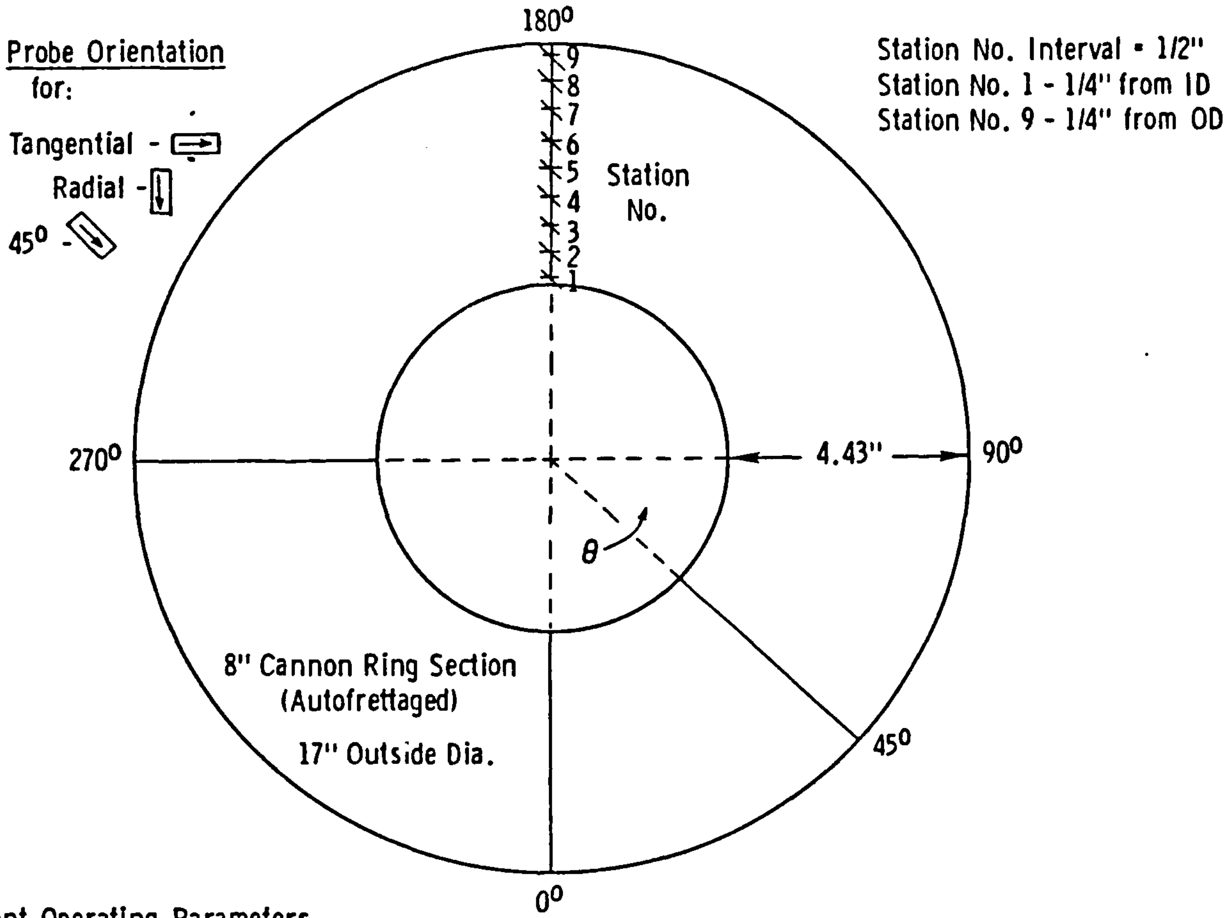
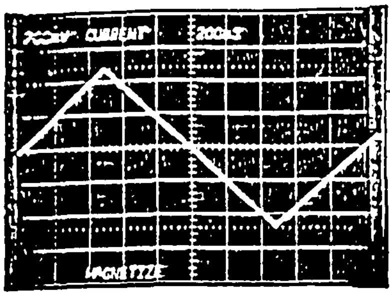


Measurement Operating Parameters:

Magnetizing Current = ±0.5 Ampere
Frequency = 0.5 Hertz
Mag Rate = 1 amp/sec
Center Detector Directly Over Station No. Point

Figure 1. Cannon ring section with measuring points.

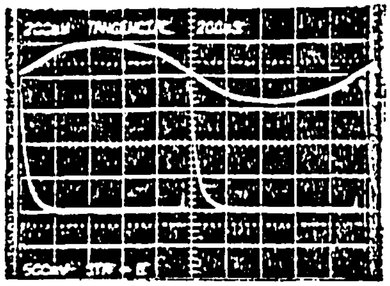


Oscilloscope records of selected measurements.

— Magnetizing current used for all measurements

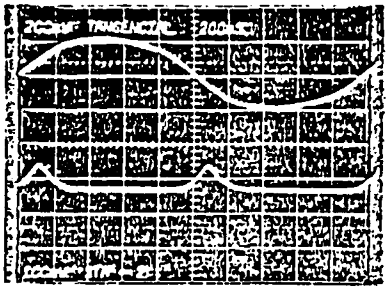
$\pm$ 500 ma (0.5 amp) - Current is measured as voltage drop ($\pm$ 500 mv) across 1 Ω resistor in series with mag. coil.

Period for 1 cycle = 2 seconds (f = 0.5 Hz)



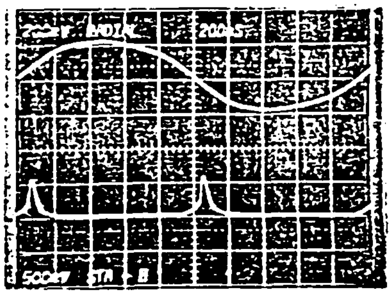
Station #8 (Tangential) - High Tensile Stress   Station #2 (Tangential) - High Compressive

Both records: Upper trace (200 mv/div), Actual Field @0.5 G/mv; Lower trace (500 mv) Bark. Ampl.

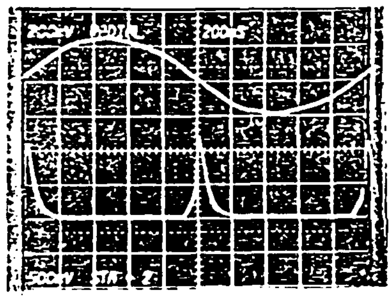


— Station #2 again (Tangential) but at 5X higher gain as above sens = 100mv/div. Recordings show over 30X dynamic range from high compression to high tension.

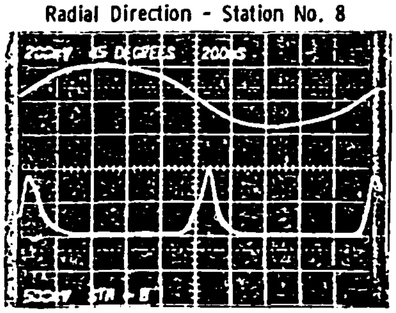
Figure 2. Oscilloscope records.



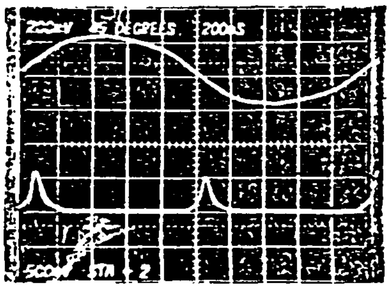
Radial Direction - Station No. 8



Radial Direction - Station No. 2



45^{0} Direction - Station No. 8



45^{0} Direction - Station No. 2

Figure 3. High tension versus high compression.

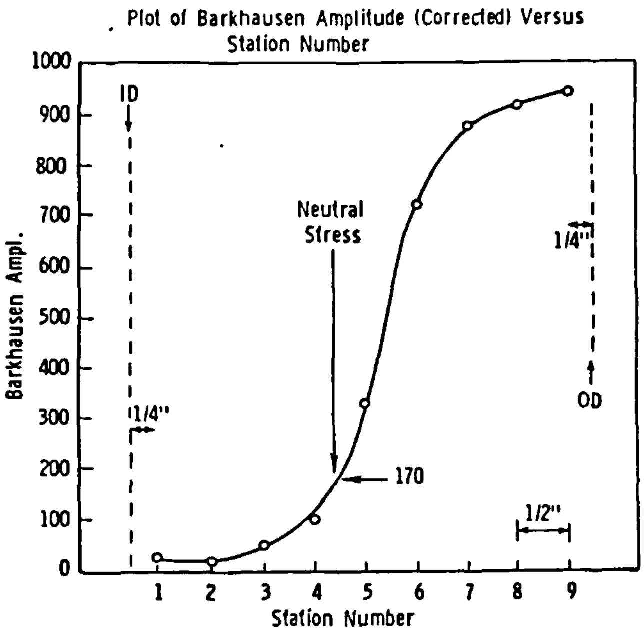


Figure 4. Barkhausen amplitude versus station number.

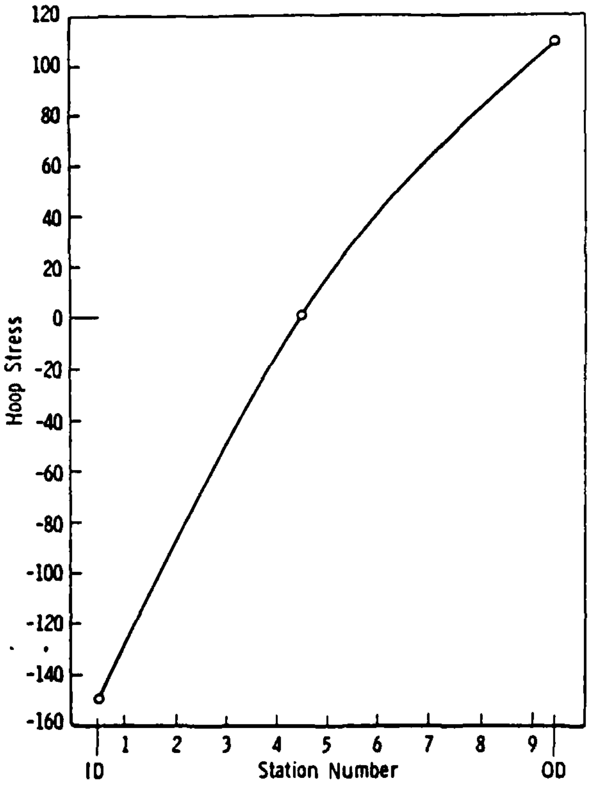


Figure 5. Hoop stress versus station number.

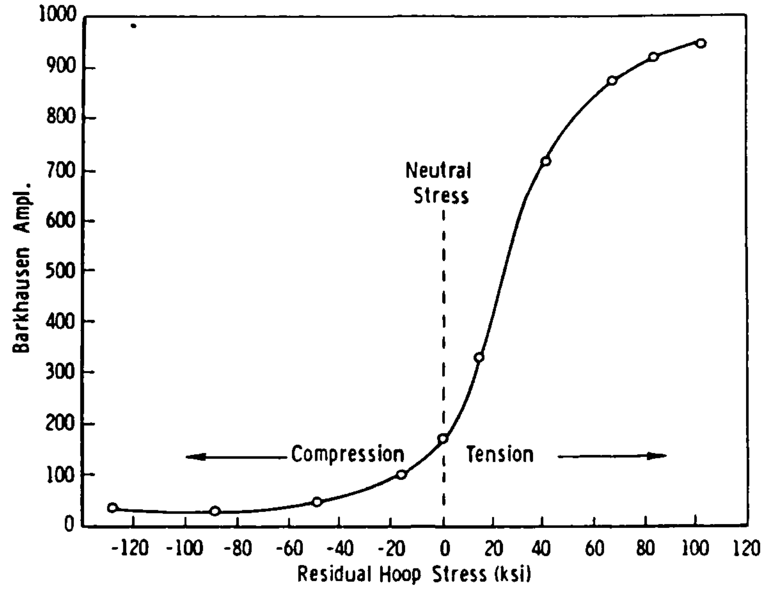
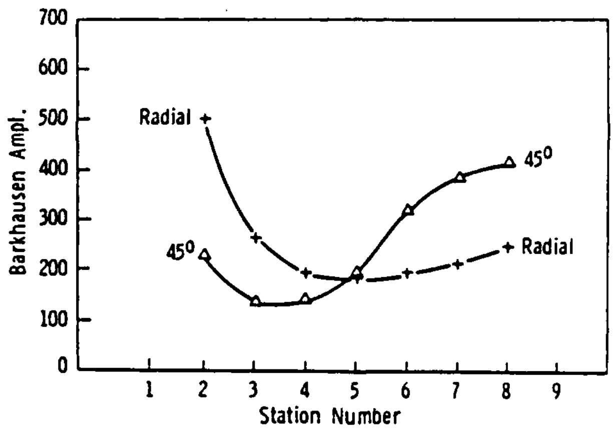


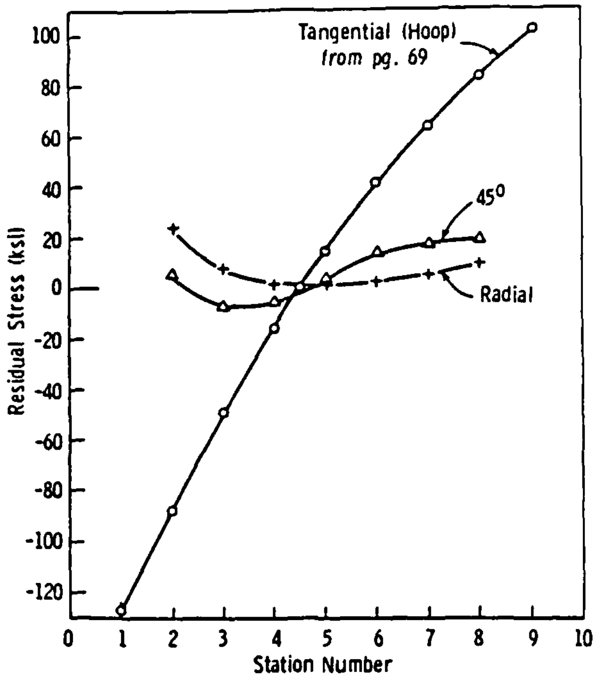
Figure 6. Barkhausen amplitude versus residual hoop stress.



Station No.	Radial Orientation Barkhausen Ampl.	45° Orientation Barkhausen Ampl.
1	*	*
2	505	224
3	261	134
4	194	140
5	187	191
6	197	316
7	211	383
8	246	414
9	*	*

*No measurement: Probe pole pieces extend beyond ID & OD at 1 & 9, respectively.

Figure 7. Radial orientation versus 45° orientation.



Station No.	Residual Stress (ksi)	45° Stress
2	+25	+6
3	+9	-8
4	+2	-6
5	+1	+2
6	+3	+13
7	+5	+17
8	+9	+19

Figure 8. Residual stress versus station number.

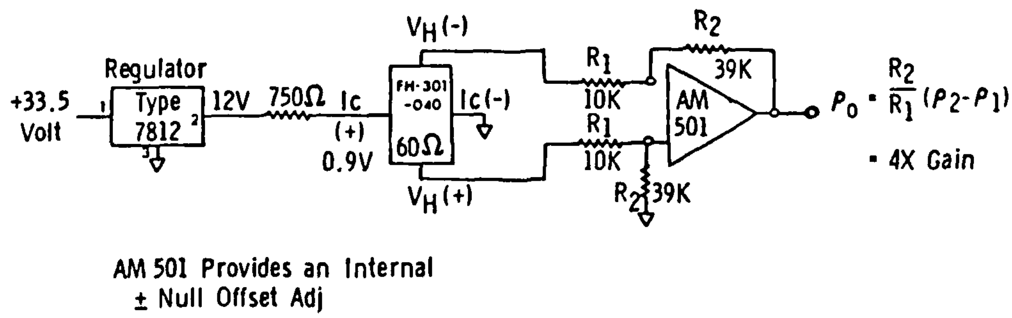
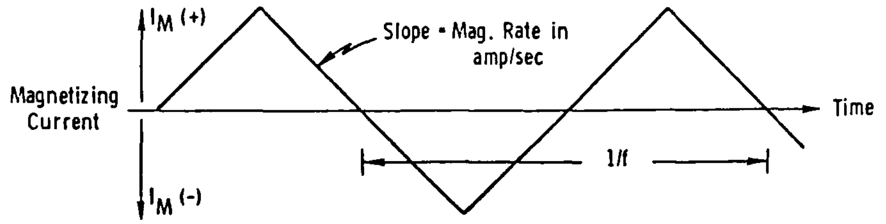


Figure 9. Schematic of Hall Amplifier.



At Constant Mag. Rate = 1 amp/sec

Current Ampl. (I_M)	Mag. Rate (amp/sec)	Freq.	ATTN	Barkhausen Ampl.
±0.125 amp	0.125 amp/0.125 sec = 1	2 Hz	5	1095
±0.25 amp	0.25 amp/0.25 sec = 1	1 Hz	5	1100
±0.50 amp	0.50 amp/0.50 sec = 1	0.50 Hz	5	1100
±0.75 amp	0.75 amp/0.75 sec = 1	0.333 Hz	5	1090
±1.0 amp	1.0 amp/1.0 sec = 1	0.25 Hz	5	1080
	At Constant Current = ±0.5 amp			
±0.5 amp	0.2 amp/sec	0.1 Hz	5	580
±0.5 amp	0.5 amp/sec	0.25 Hz	5	850
±0.5 amp	1.0 amp/sec	0.50 Hz	5	1100
±0.5 amp	1.5 amp/sec	0.75 Hz	5	1200
±0.5 amp	2.0 amp/sec	1.0 Hz	5	1270
±0.5 amp	4.0 amp/sec	2.0 Hz	5	1320

Figure 10. Magnetizing rate.

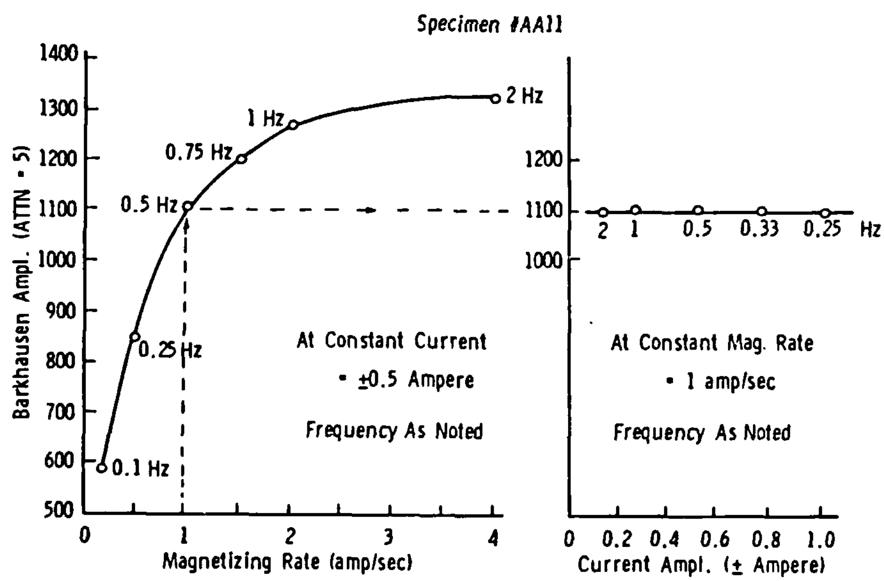
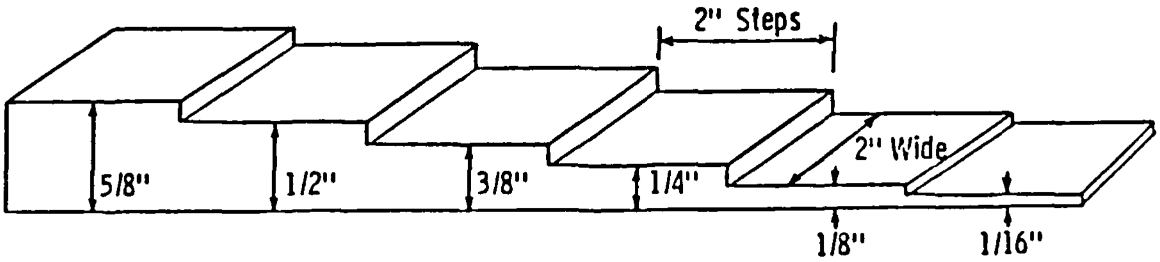


Figure 11. Barkhausen amplitude versus magnetizing rate.



Step Thick.	Step Side ∥	Step Side ⊥	Flat Side ∥	Flat Side ⊥	Corrected Readings Step Side ∥	Corrected Readings Step Side ⊥	Corrected Readings Flat Side ∥	Corrected Readings Flat Side ⊥
5/8"	434	352	853	263	177	136	386	91
1/2"	400	732	995	252	160	326	457	86
3/8"	490	498	1040	287	205	209	480	103
1/4"	425	695	1170	280	172	307	545	100
1/8"	442	1070	803	385	181	495	361	152
1/16"	575	834	1020	525	247	377	470	222

Figure 12. Step block.

Records of Barkhausen Response at Step Thickness • 3/8", 1/4", 1/8", & 1/16"
Oscilloscope Vertical Sensitivity • 0.5 v/div.

Step Side (||) Step Side (⊥)

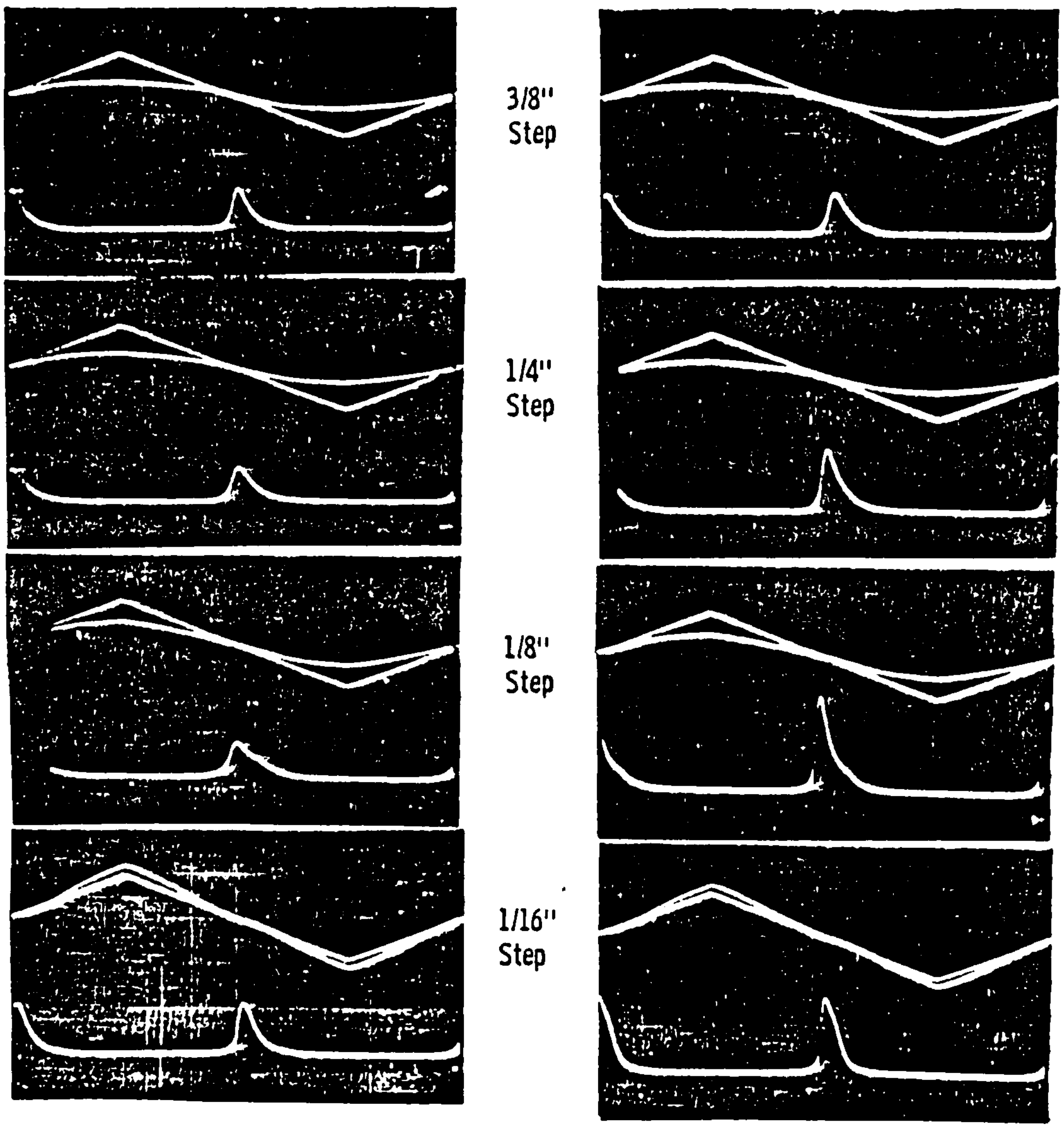


Figure 13. Barkhausen responses of step block.

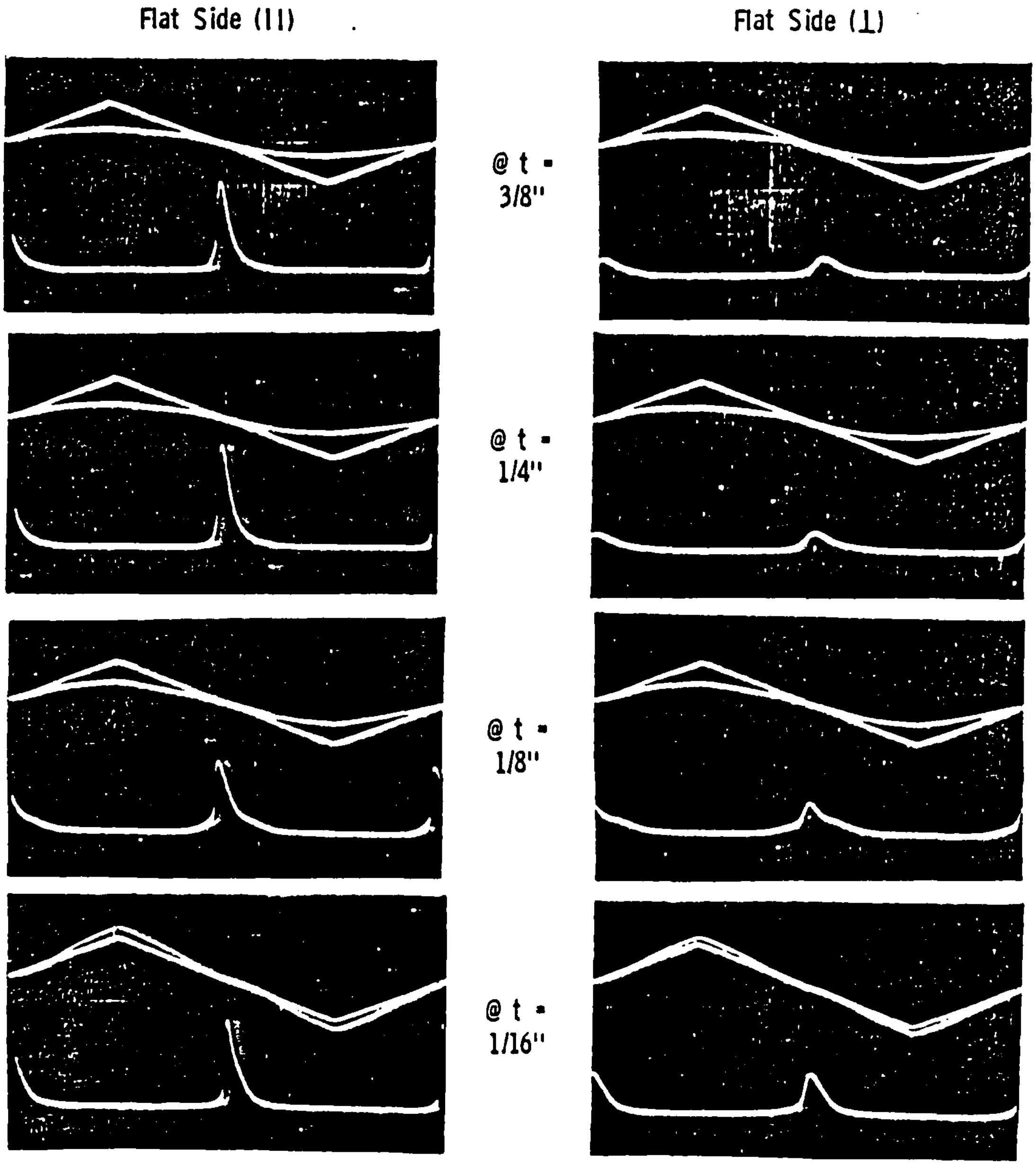


Figure 14. Barkhausen responses of step block.

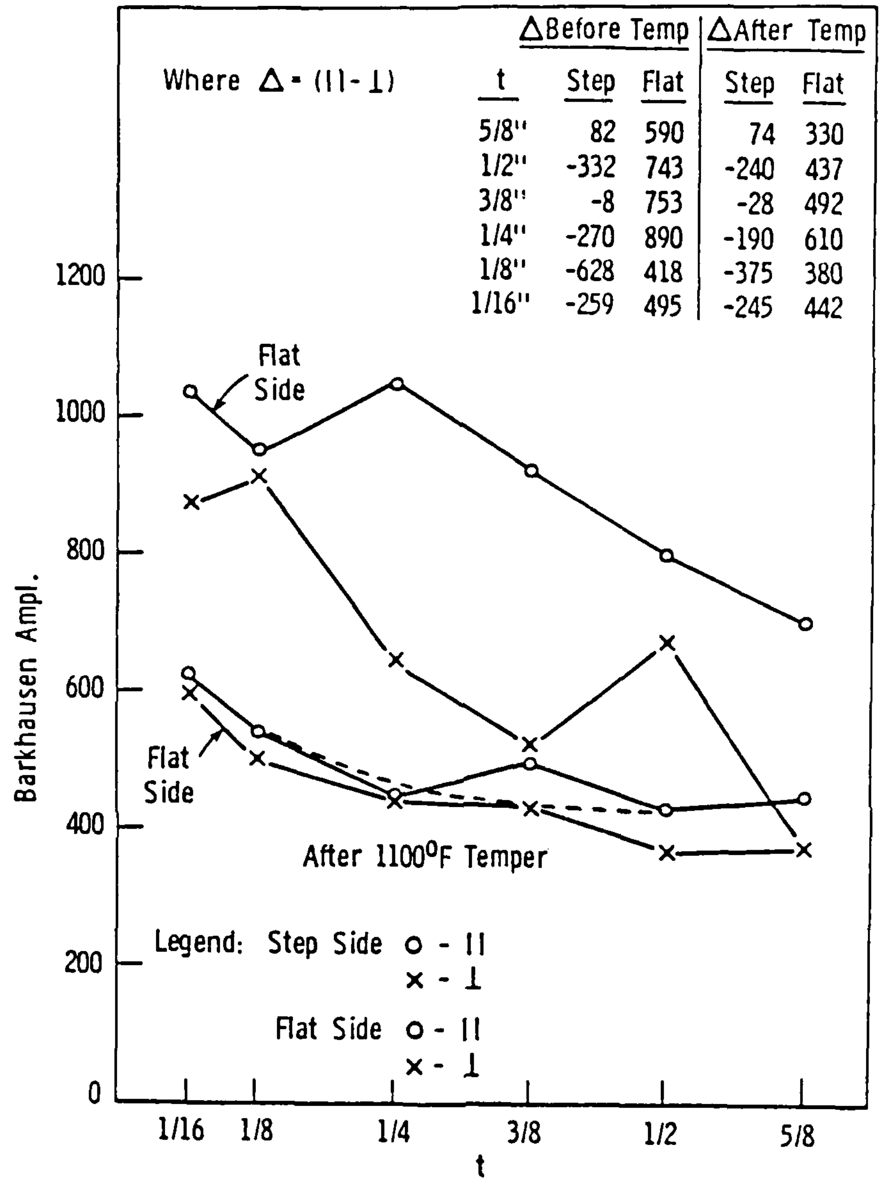


Figure 15. Results of step block study.

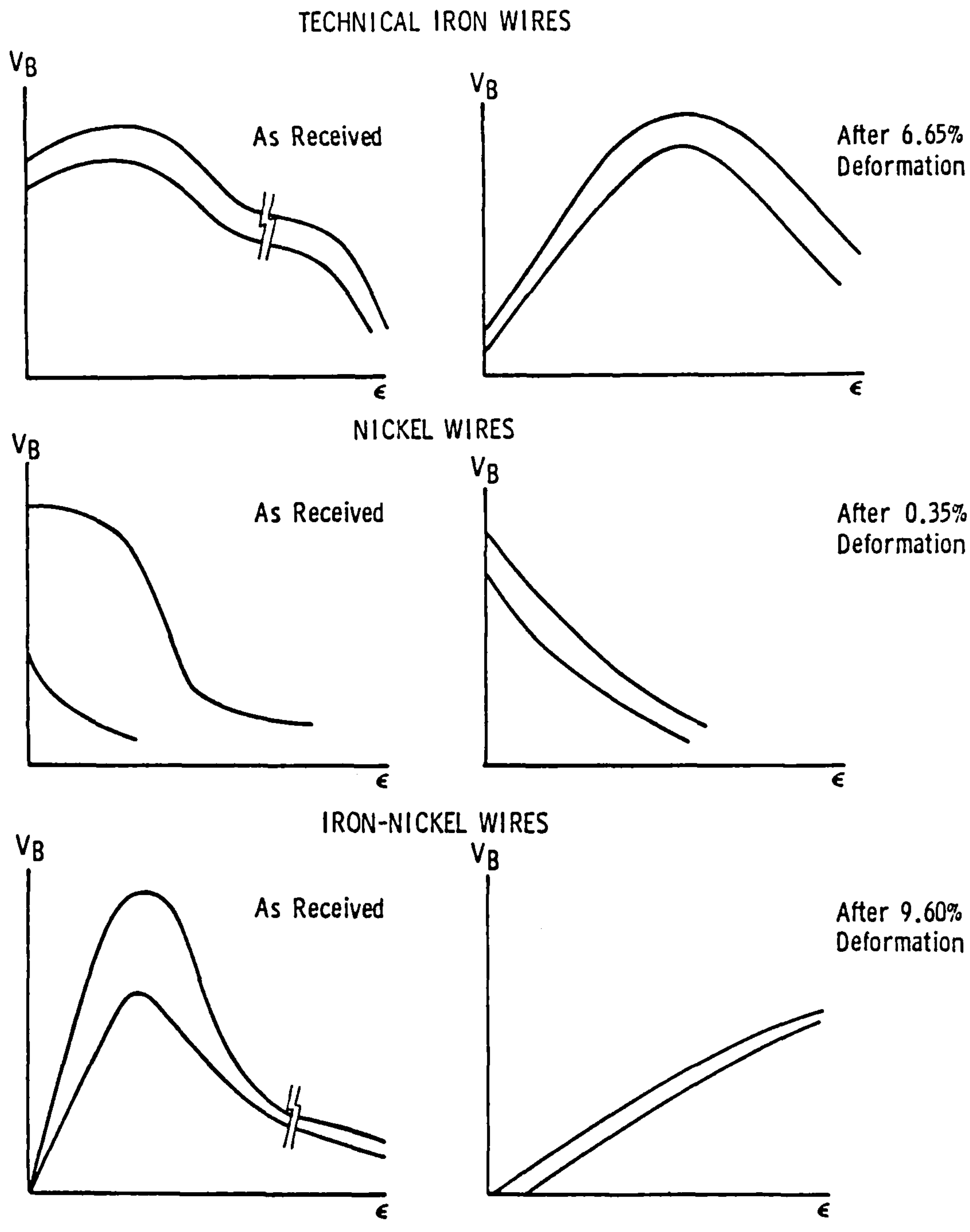
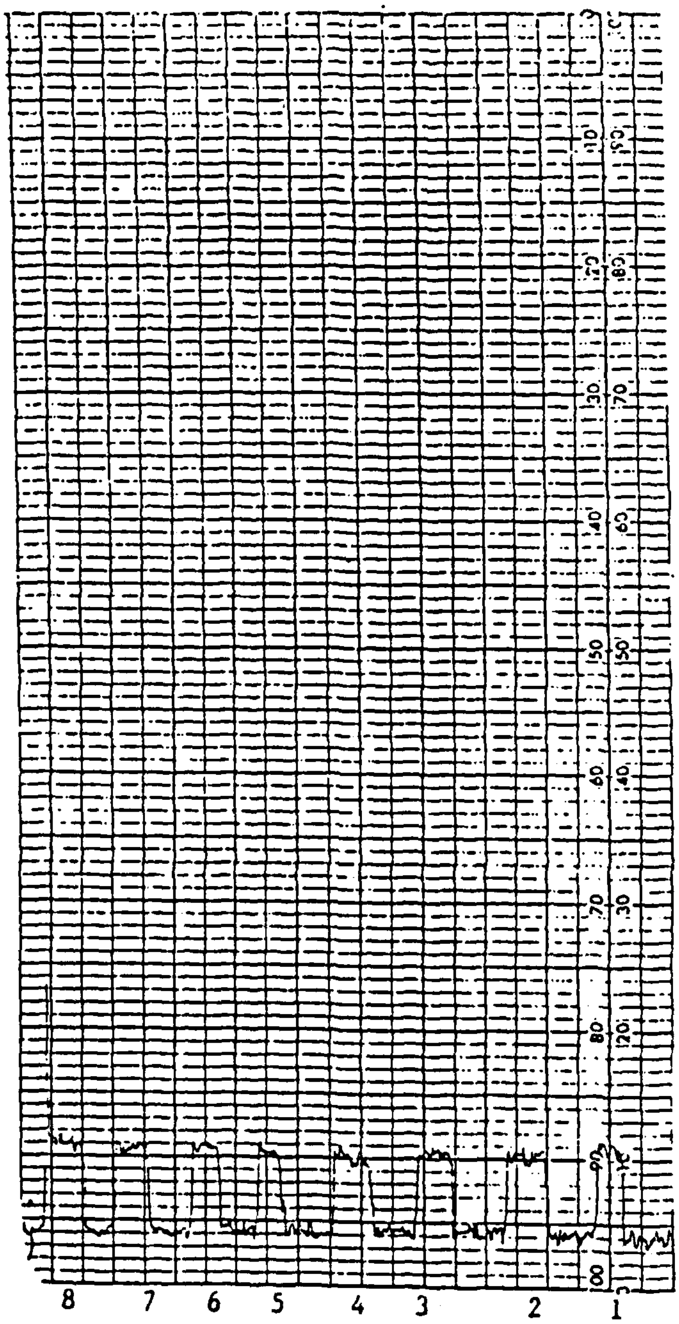
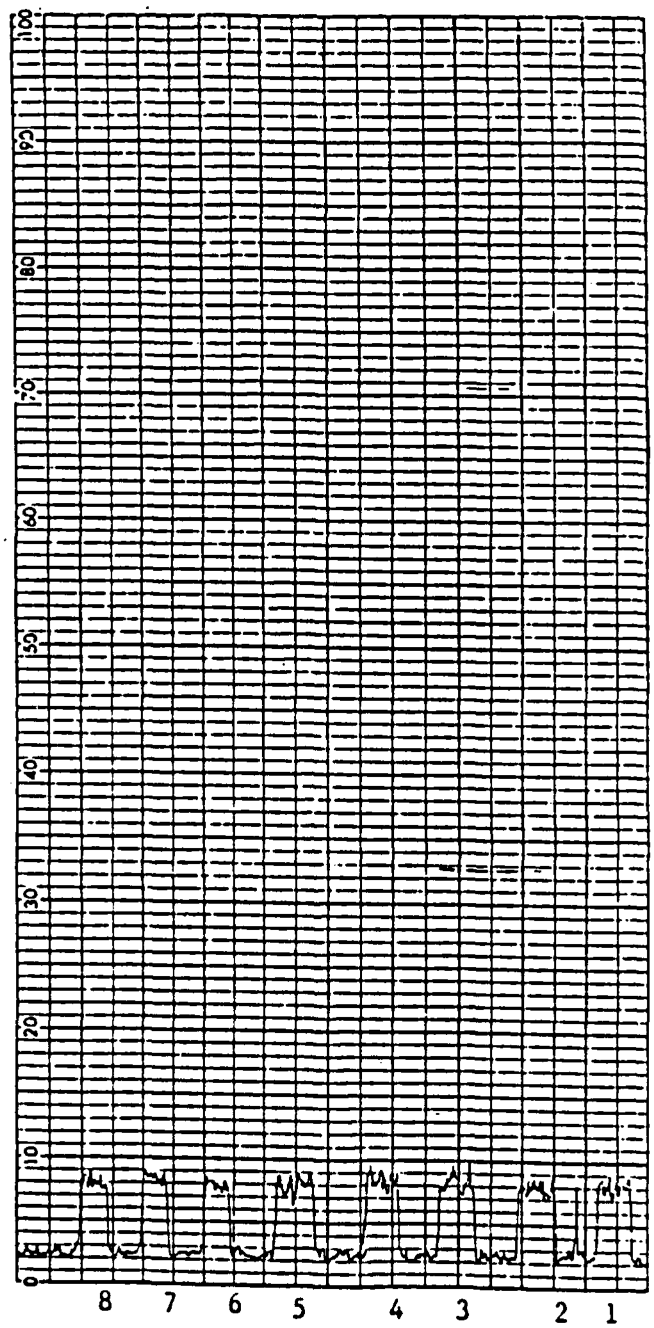


Figure 16. Technical iron wires.



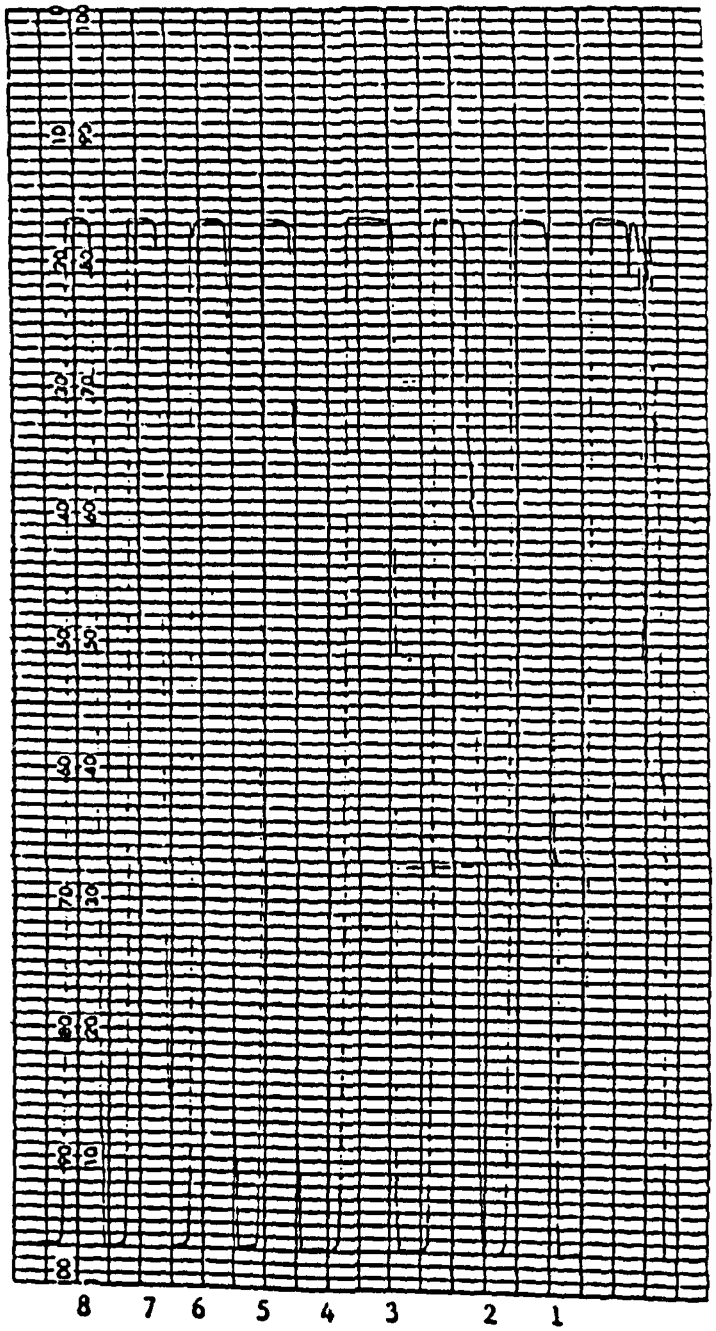
ID inspection of large part
Depth of measurement = approximately 0.02 mm
Measurement direction - circumferential

Figure 17. Large part, ID, circumferential, 0.02 mm.



ID inspection of large part
Depth of measurement = approximately 0.07 mm
Measurement direction - circumferential

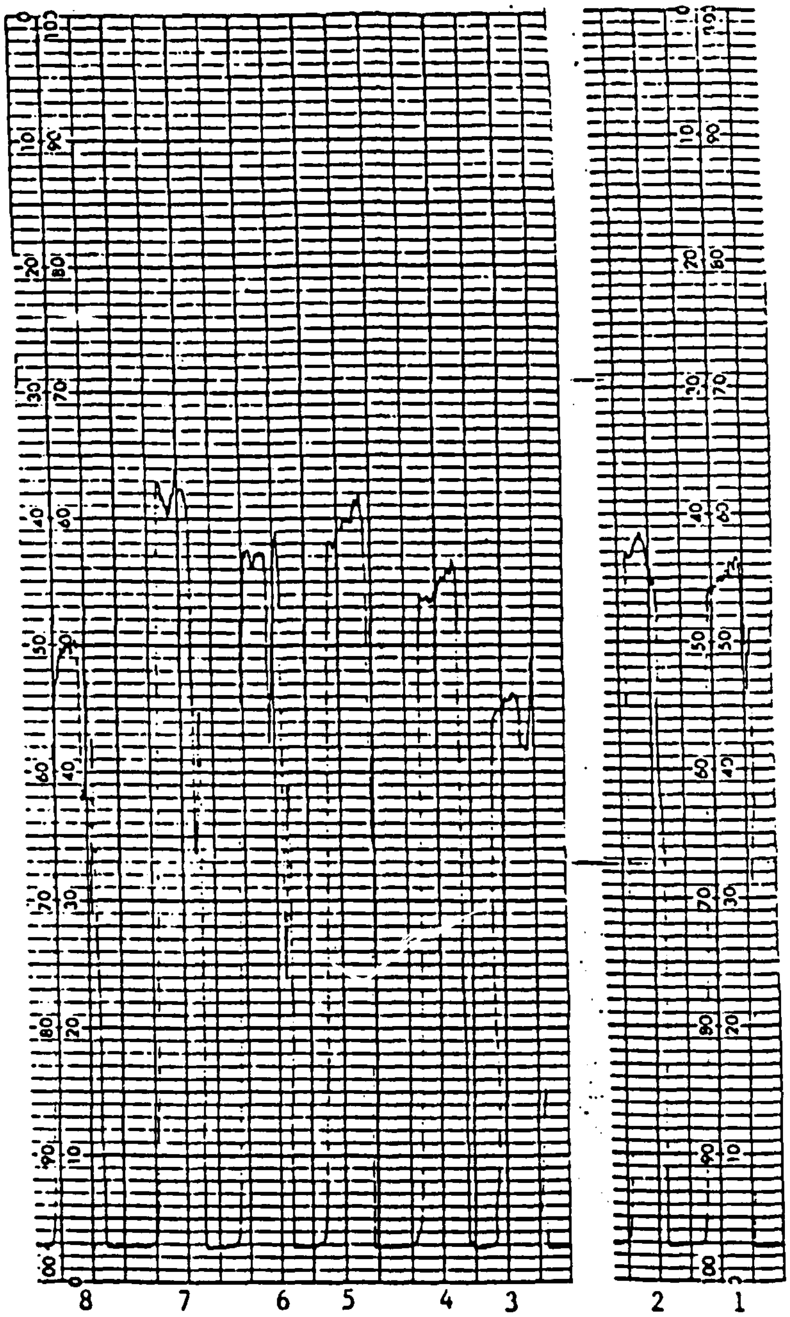
Figure 18. Large part, ID, circumferential, 0.07 mm.



ID inspection of large part
Depth of measurement = approximately 0.02 mm
Measurement direction - transverse

NOTE: The recorded output shown above is 1/5 of the actual readings.

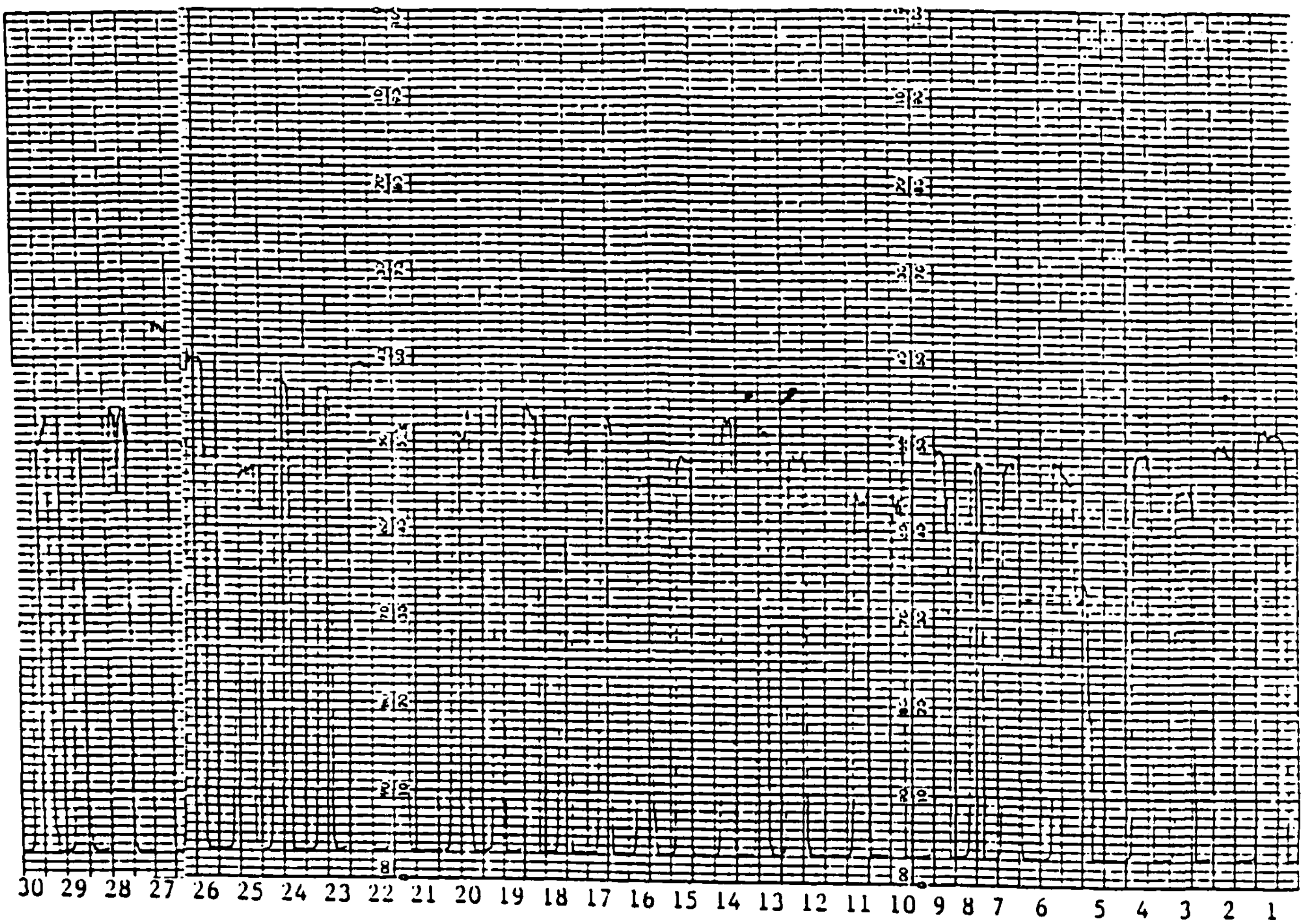
Figure 19. Large part, ID, transverse, 0.02 mm.



ID inspection of large part
Depth of measurement = approximately 0.07 mm
Measurement direction - transverse

NOTE: The recorded output shown above is 1/5 of the actual readings.

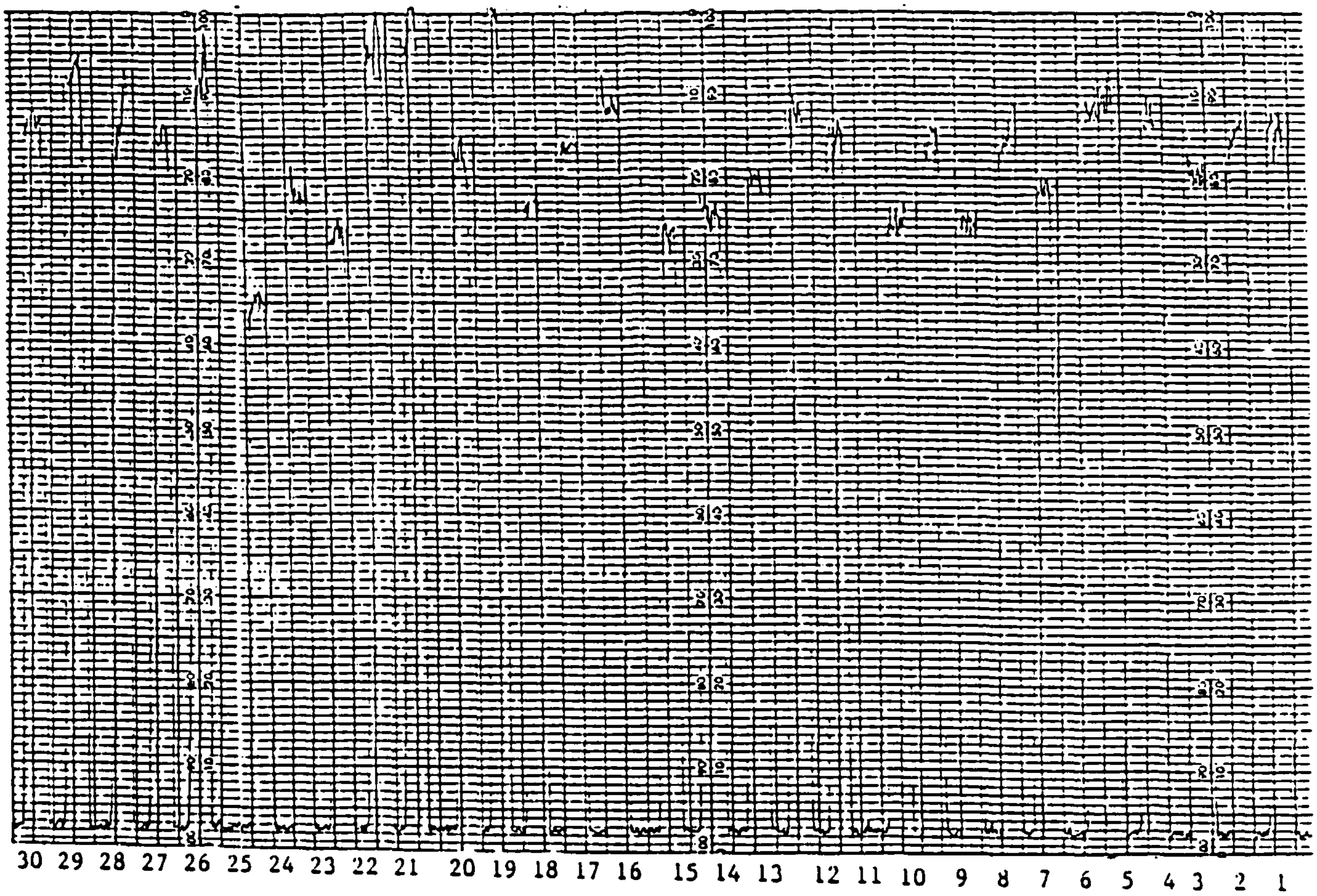
Figure 20. Large part, ID, transverse, 0.07 mm.



OD inspection of large part
Depth of measurement = approximately 0.02 mm
Measurement direction - circumferential

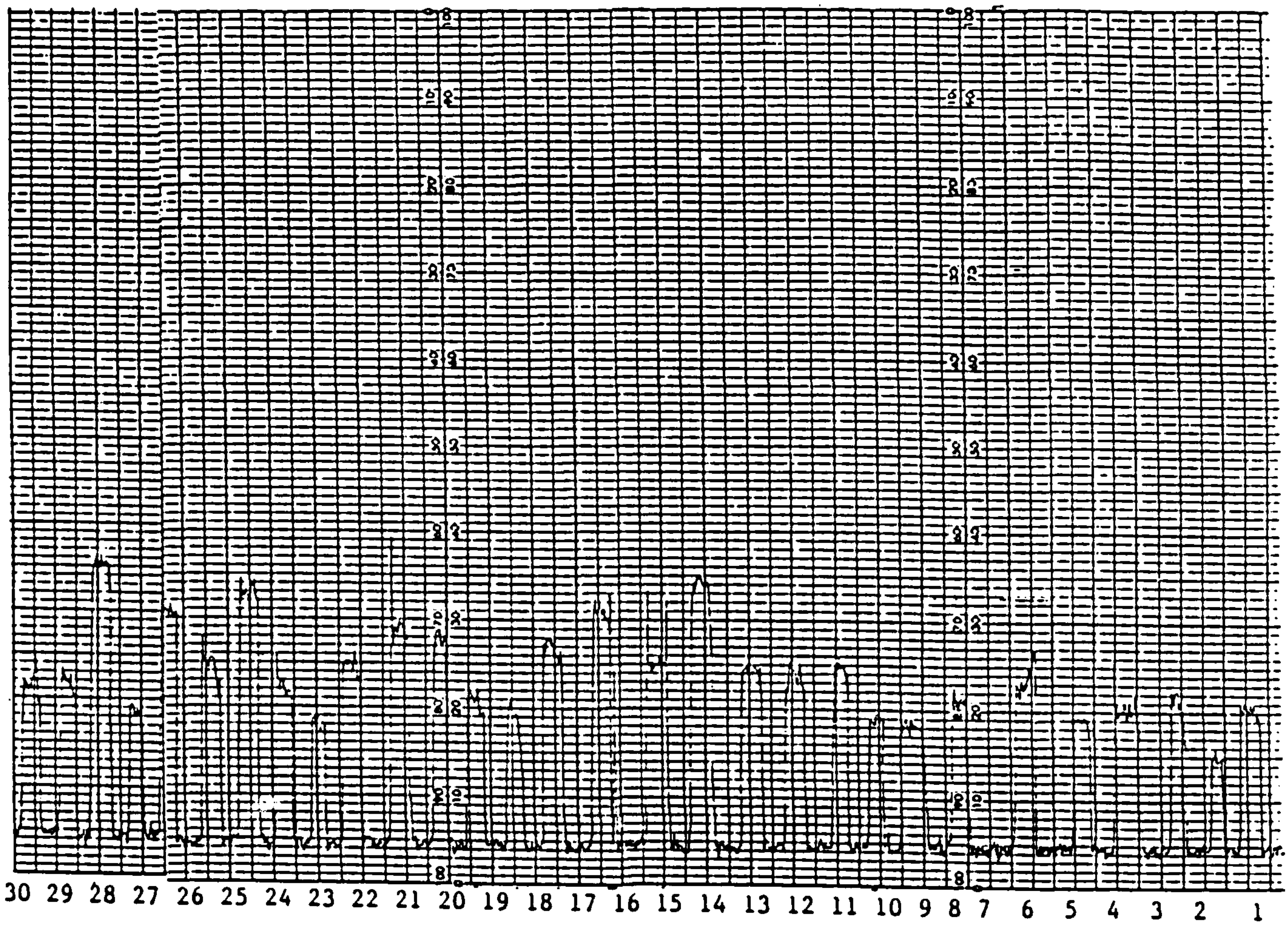
NOTE: The recorded output shown above is 1/5 of the actual readings.

Figure 21. Large part, OD, circumferential, 0.02 mm.



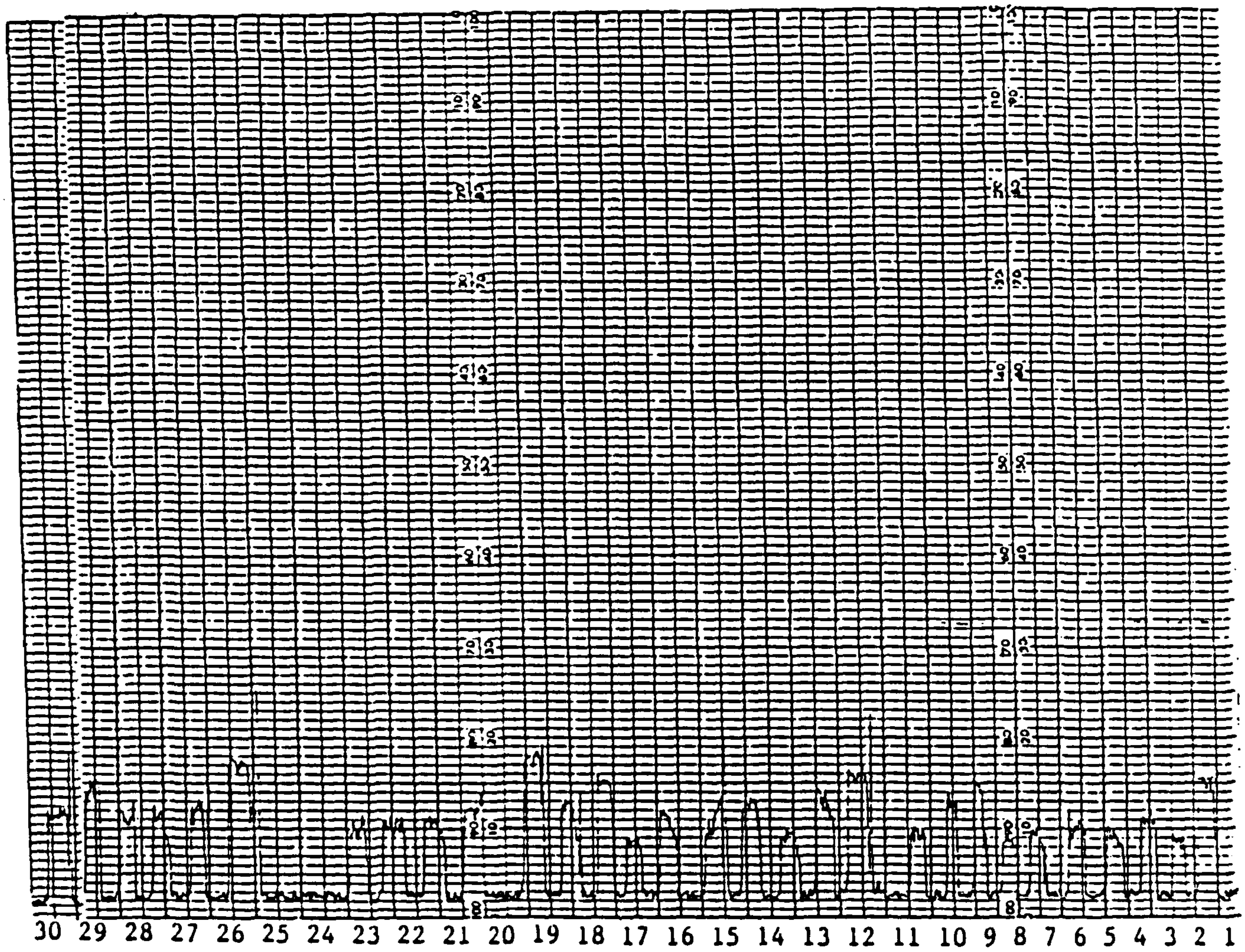
OD inspection of large part
Depth of measurement = approximately 0.07 mm
Measurement direction - circumferential

Figure 22. Large part, OD, circumferential, 0.07 mm.



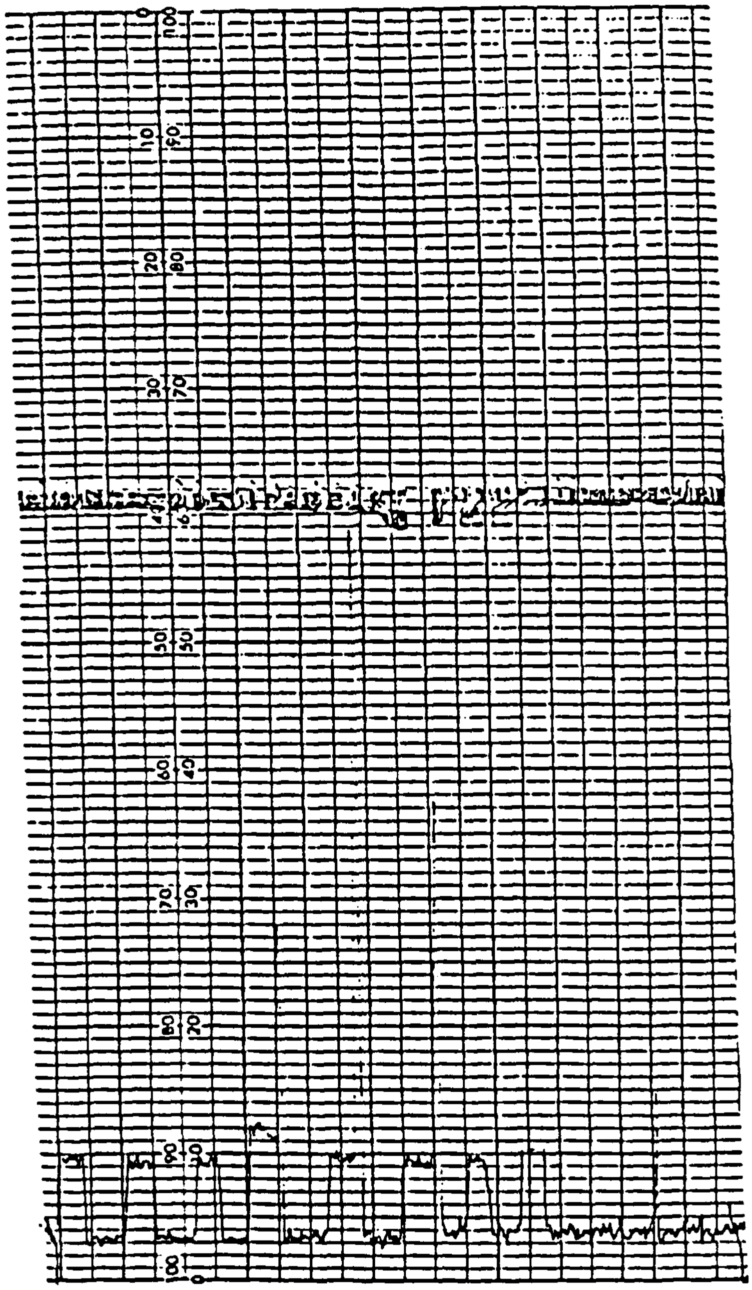
OD inspection of large part
Depth of measurement = approximately 0.02 mm
Measurement direction - transverse

Figure 23. Large part, OD, transverse, 0.02 mm.



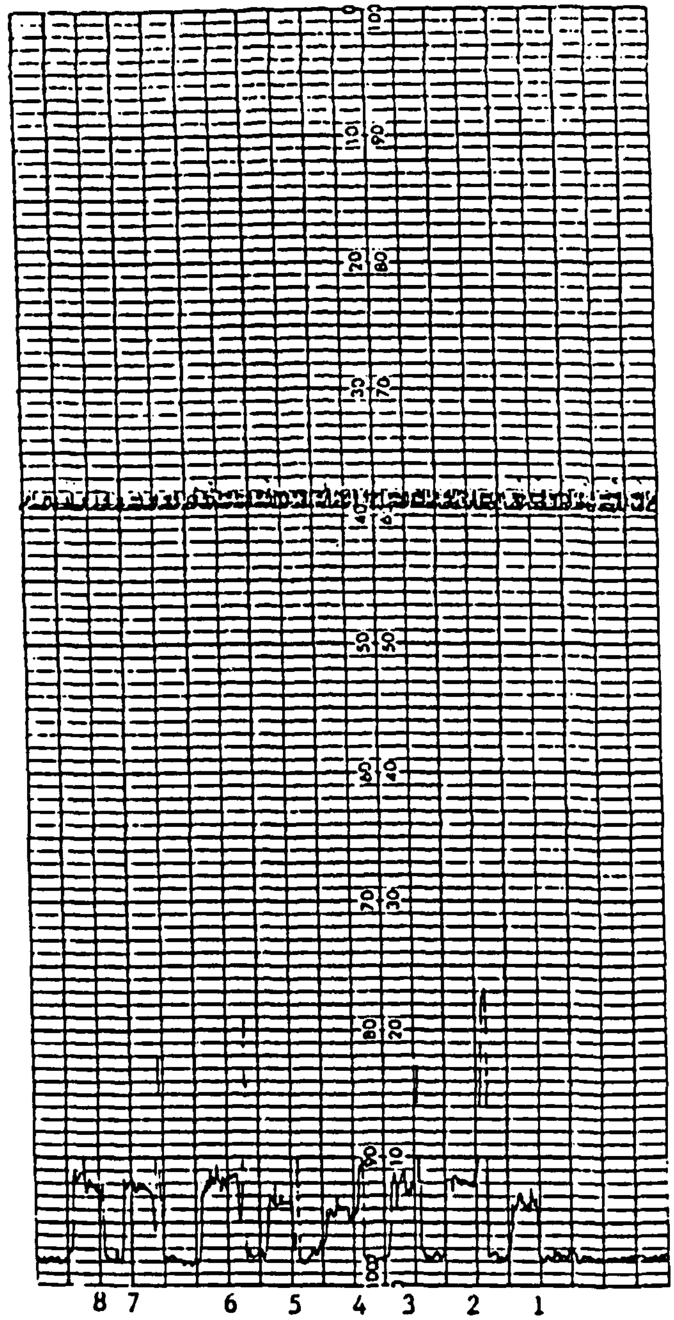
OD inspection of large part
Depth of measurement = approximately 0.07 mm
Measurement direction - transverse

Figure 24. Large part, OD, transverse, 0.07 mm.



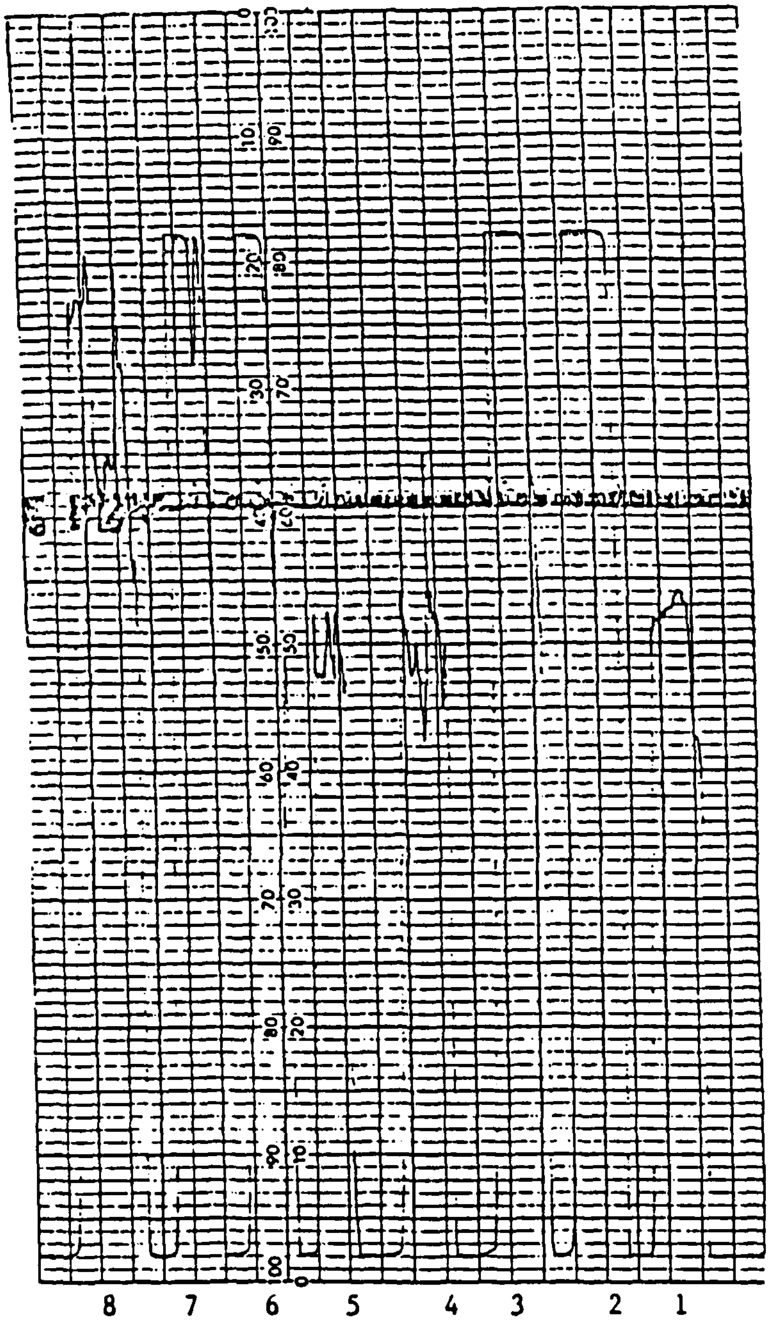
ID inspection of small part
Depth of measurement = approximately 0.02 mm
Measurement direction - circumferential

Figure 25. Small part, ID, circumferential, 0.02 mm.



ID inspection of small part
Dept of measurement = approximately 0.07 mm
Measurement direction - circumferential

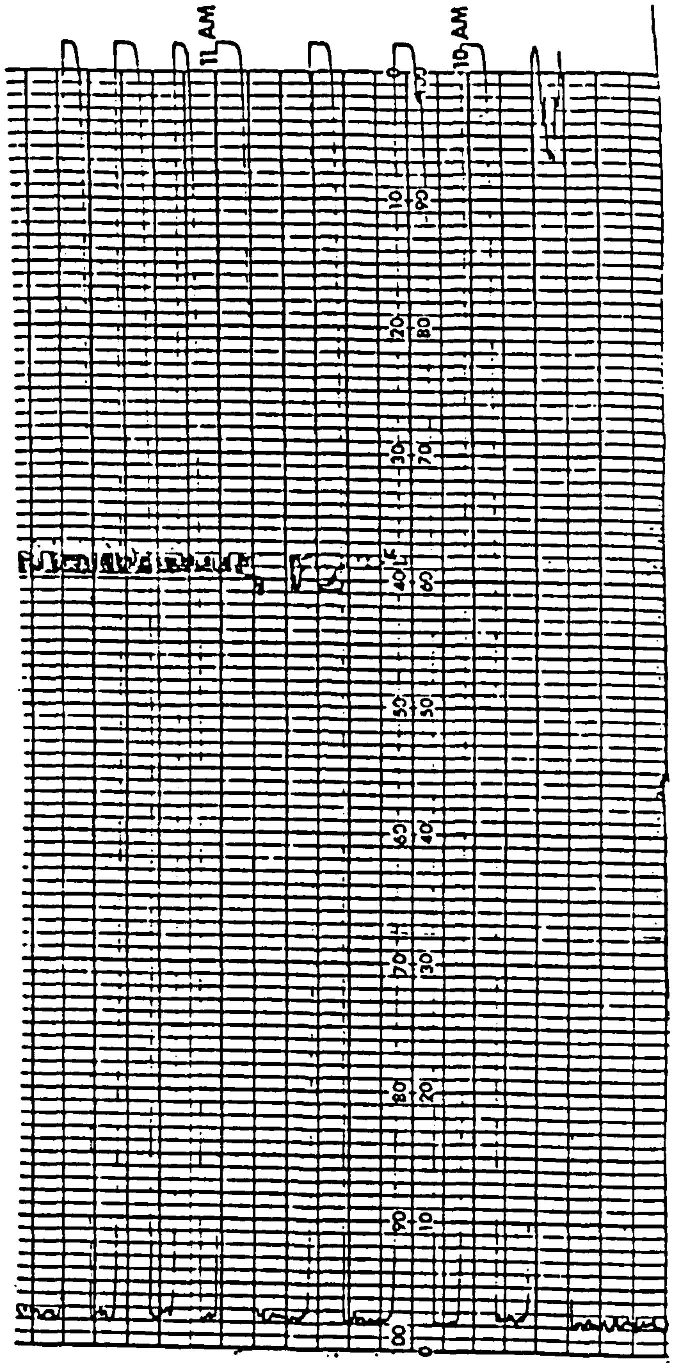
Figure 26. Small part, ID, circumferential, 0.07 mm.



ID inspection of small part
Depth of measurement = approximately 0.02 mm
Measurement direction - transverse

NOTE: The recorded output shown above is 1/5 of the actual readings.

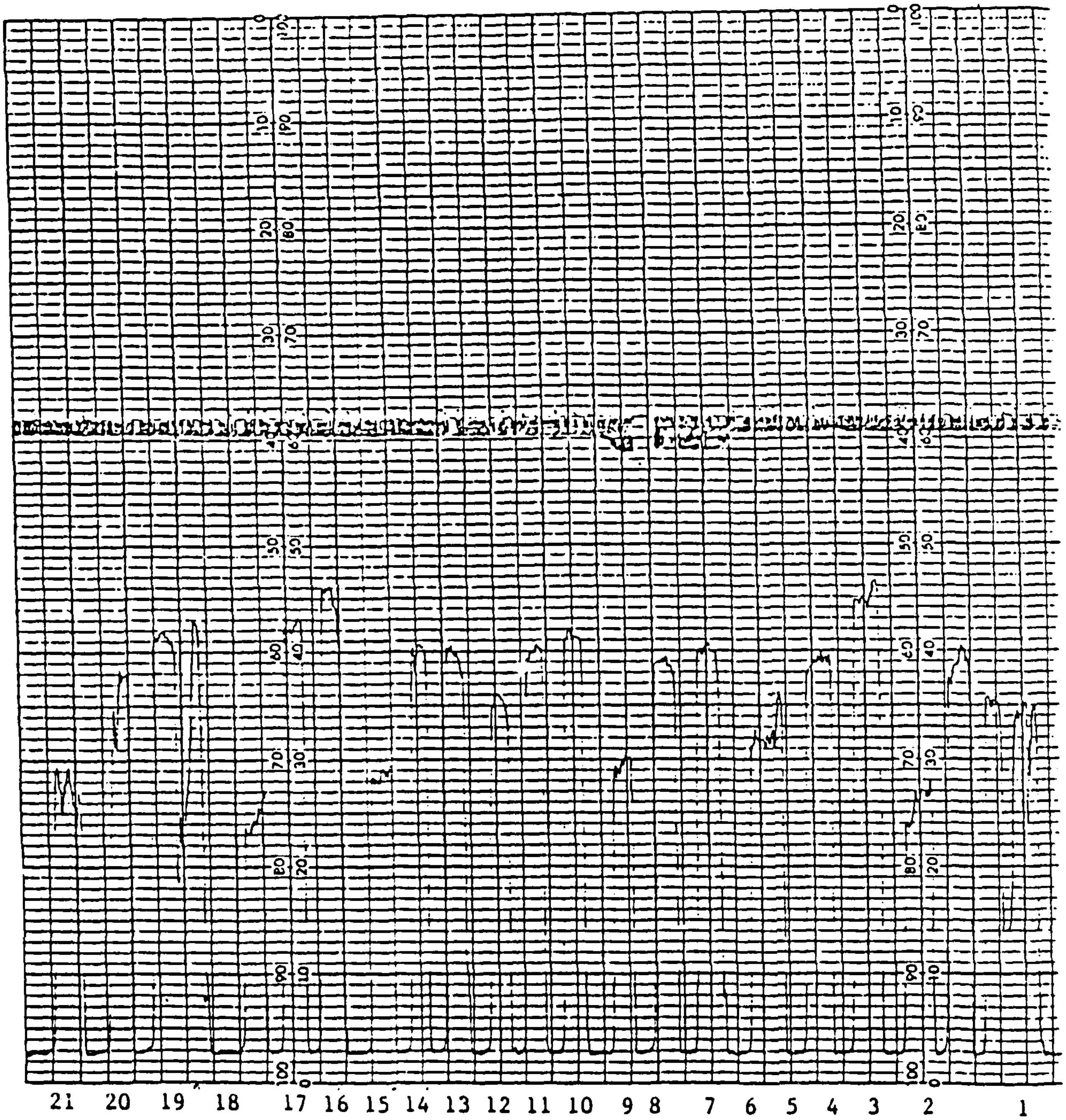
Figure 27. Small part, ID, transverse, 0.02 mm.



8 7 6 5 4 3 2 1

ID inspection of small part
Depth of measurement = approximately 0.07 mm
Measurement direction - transverse

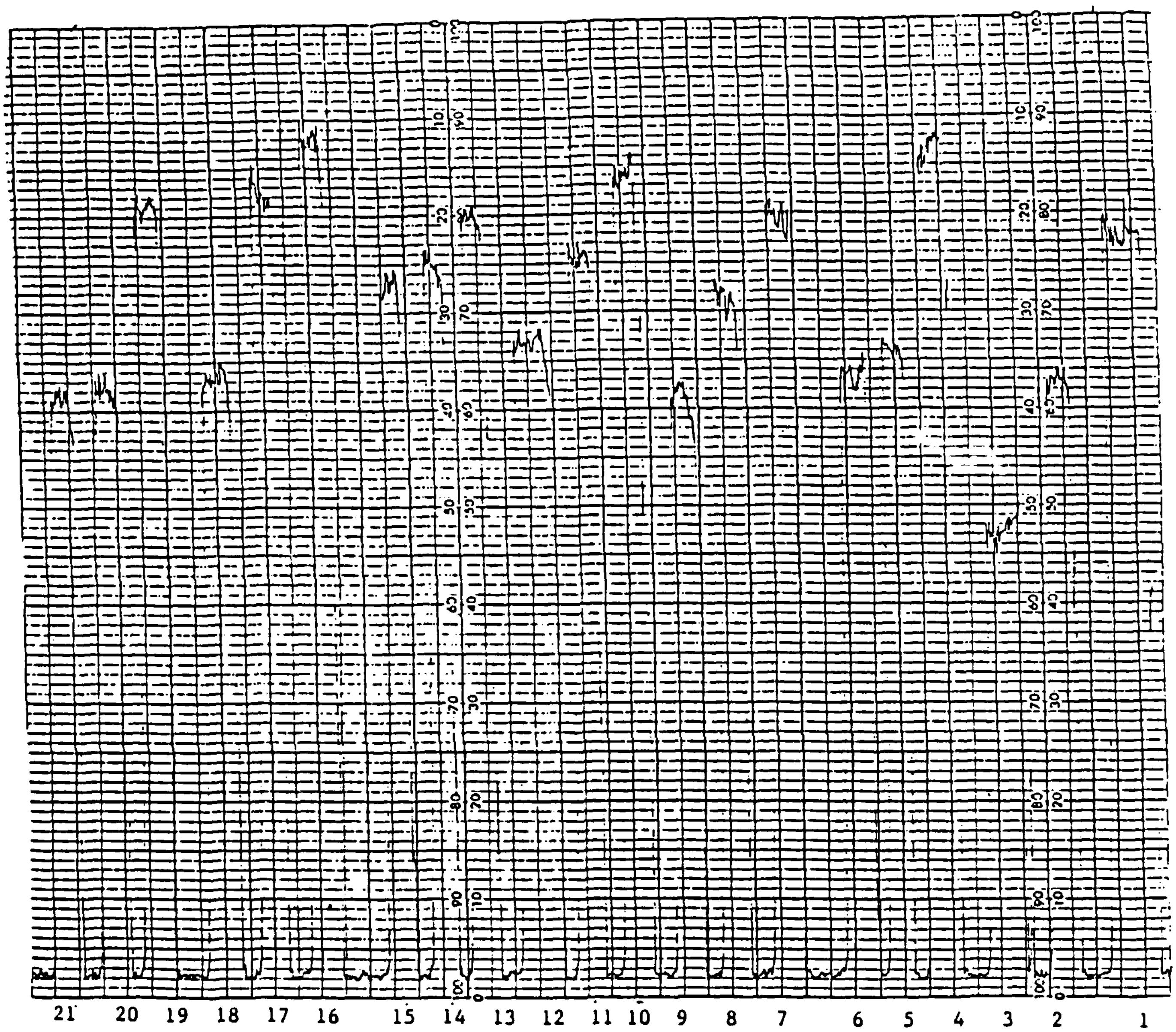
Figure 28. Small part, ID, transverse, 0.07 mm.



OD inspection of small part
Depth of measurement = approximately 0.02 mm
Measurement direction - circumferential

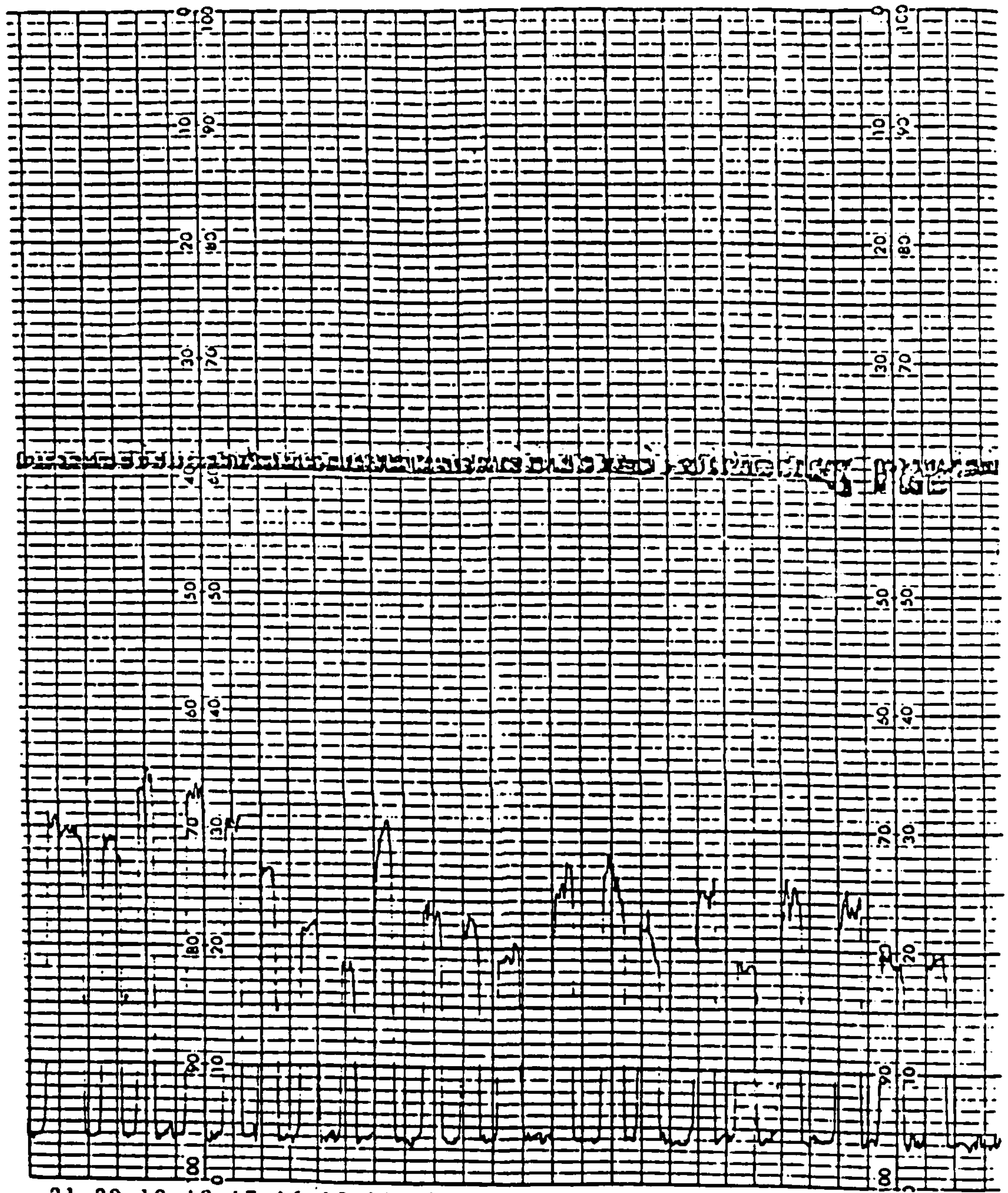
NOTE: The recorded output shown above is 1/5 of the actual readings.

Figure 29. Small part, OD, circumferential, 0.02 mm.



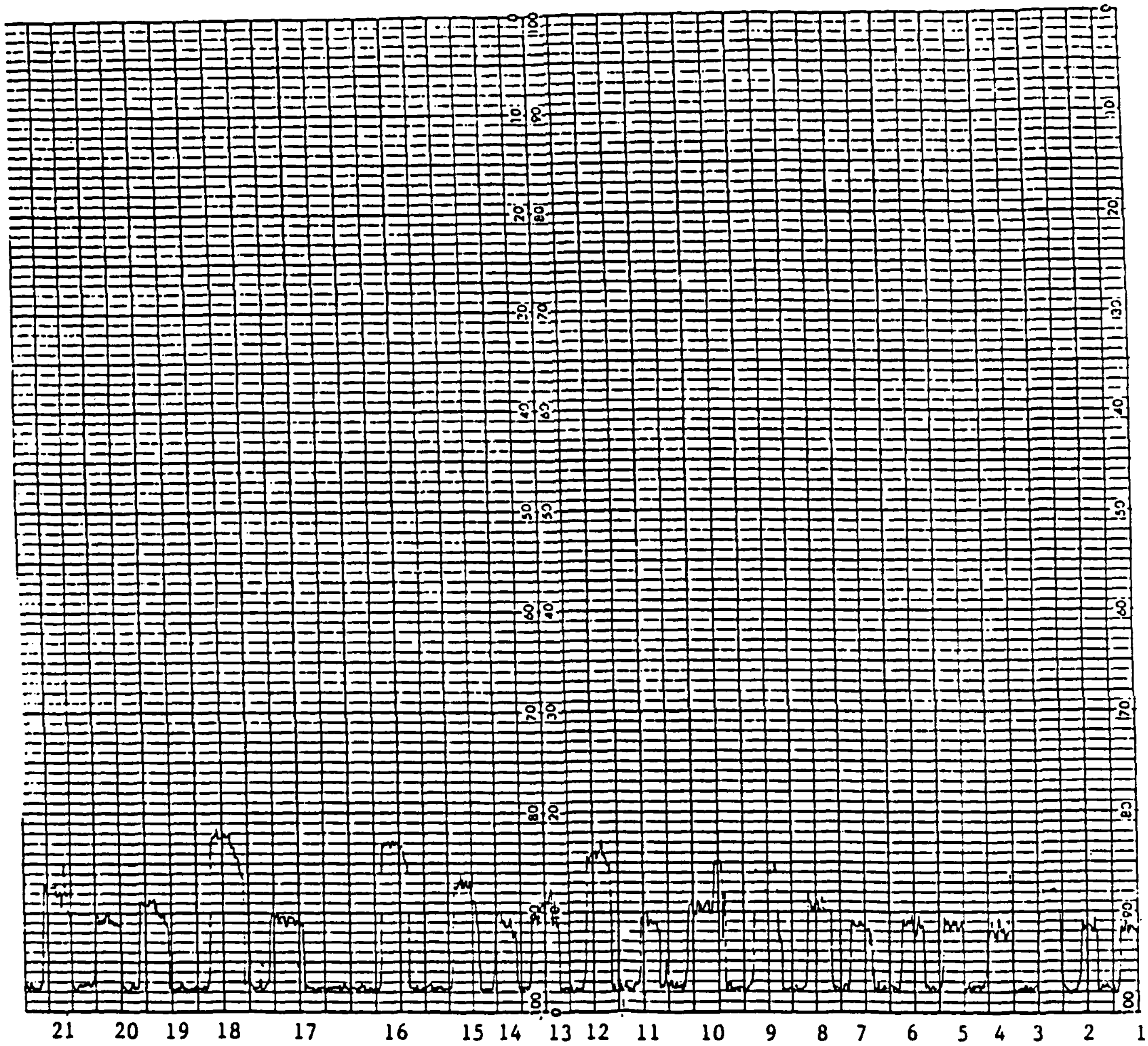
OD inspection of small part
Depth of measurement = approximately 0.07 mm
Measurement direction - circumferential

Figure 30. Small part, OD, circumferential, 0.07 mm.



OD inspection of small part
Depth of measurement = approximately 0.02 mm.
Measurement direction - transverse

Figure 31. Small part, OD, transverse, 0.02 mm.



OD inspection of small part
Depth of measurement = approximately 0.07 mm
Measurement direction - transverse

Figure 32. Small part, OD, transverse, 0.07 mm.

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	Commander, U.S. Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, OH 45433
1	ATTN: AFWAL/MLC
1	AFWAL/MLLP, M. Forney, Jr.
1	AFWAL/MLBC, Mr. Stanley Schulman
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, AL 35812
1	ATTN: R. J. Schwinghammer, EH01, Dir, M&P Lab
1	Mr. W. A. Wilson, EH41, Bldg. 4612
	U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, MD 20899
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	Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001
2	ATTN: SLCMT-TML
1	Author

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
BARKHAUSEN NOISE ANALYSIS AND FERROMAGNETIC MATERIALS -
Douglas J. Strand

Technical Report MTL TR 89-108, December 1989, 43 pp-illus-tables, D/A Project: 1L162105.AH84

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At its foundations (ferromagnetic domains), the Barkhausen effect has a rich theory. An introduction to this theory is first given. The Barkhausen effect is defined and a description of how it comes about is given. Barkhausen Noise Analysis (BNA) is used as a nondestructive evaluation method. Completed applications of this are cited and explained. BNA is applicable only to *ferromagnetic materials*, so its use has *primarily focused* on *armor* applications in this study. The parameters which affect the method were also sought and the results given.

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