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ADVANCED SIGNAL ANALYSIS AND INSTRUMENTATION FOR BARKHAUSEN STRESS MEASUREMENT IN STEELS

September 1977

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Advanced methods of signal analysis were investigated as a means of improving instrumentation for Barkhausen noise stress measurement. Methods employed included pulse-sorting and pulse-counting, correlation and probability measurements, and spectrum analysis. Specimens of AISI 4340 steel and AISI 4130 steel were studied. It was found that the Barkhausen noise auto-correlation function, amplitude probability distribution, and amplitude probability density correspond closely to

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the comparable functions obtained from random noise. These statistical functions were found to be independent of magnetization rate and probe liftoff but slightly dependent on stress. Cursory experiments indicated that reducing the detector bandwidth may provide a means of increasing the stress sensitivity of these parameters. Detailed analysis of processed Barkhausen noise signals and results of pulse-counting experiments indicate that the Barkhausen signal often is composed of two or more parts which respond differently to stress. Experiments on specimens stressed in uniaxial tension and cantilever bending showed that the shapes of the Barkhausen signals and the statistical characteristics depend upon the mode of loading. Based on the results of this program, an improved Barkhausen stress measuring instrument was developed, fabricated, and delivered to the Army Materials and Mechanics Research Center.

FOREWORD

This project has been accomplished as part of the U.S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures or prototype equipment in nondestructive testing to insure efficient inspection methods for materiel/material procured or maintained by DARCOM.

The project was performed by the Southwest Research Institute under Contract DAAG46-76-C-0028 to the U.S. Army Materials and Mechanics Research Center. Appreciation is expressed to the Contracting Officers Technical Representative, Mr. Harold Hatch, DRXMR-MI, for his technical guidance and cooperation throughout the performance of this program.

This report covers work performed under Phases I and II of the project. In Phase III, a portable Barkhausen Noise Stress Measurement System was fabricated and delivered to the Army Materials and Mechanics Research Center along with an Instruction Manual describing its operation.

The Project Manager for this program was G. A. Matzkanin; much of the experimental work was performed by G. L. Burkhardt. Special thanks are due W. D. Perry and E. H. Cooper for considerable assistance in the design and fabrication of the Barkhausen Stress Measuring Instrument.

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I. INTRODUCTION AND SUMMARY

One of the prominent problems in nondestructive evaluation is the determination of residual stress in both ferromagnetic and nonferromagnetic materials. One method which has been developed for the measurement of applied and residual stresses in ferromagnetic materials is the Barkhausen noise analysis method[1]. Refinement of this method to date has resulted in several important applications including residual stress measurements in helicopter rotor blade spars[2], autofrettaged gun tubes[3], and rolling element antifriction bearing components[4]. In at least one case, this method is being used as an alternative for X-ray diffraction[5]. Although the Barkhausen noise analysis method is being used successfully for residual stress measurement, continued development and application of the method have been impeded because in the present form of applying the method, it is difficult to compensate for the influence of factors other than stress. Such factors include probe-to-specimen liftoff, magnetization rate, specimen metallurgical constitution, and previous thermal and mechanical treatment.

Current versions of Barkhausen stress measurement instrumentation are based on analog signal processing whereby the peak amplitude of the envelope of the train of Barkhausen pulses obtained during a reversal of the specimen magnetization is used as an indication of the state of stress in the specimen. For appropriate probe orientation, high peak amplitudes are obtained when the specimen is in tension, intermediate amplitudes are obtained from stress-free specimens, and low amplitude signals are obtained when the specimen is in compression[6].

The overall objectives of the present program have been to investigate advanced methods of signal analysis for Barkhausen noise stress measurement and to develop an instrumentation system based upon the most suitable alternatives. Although previous fundamental investigations of the Barkhausen effect have involved counting and amplitude-sorting of the individual pulses composing the raw Barkhausen noise[7], the underlying statistical nature of the Barkhausen noise signal has not been adequately characterized. Therefore, a specific objective of the present program was aimed at defining and characterizing the statistics of the Barkhausen noise signal and determining how these statistical parameters are influenced by stress, probe liftoff, magnetization rate and specimen metallurgical constitution and microstructure. It was anticipated that this investigation would lead to improved methods for residual stress measurements substantially expanding application of the Barkhausen noise approach to the nondestructive determination of stress in ferromagnetic materials.

The approach utilized in this program involved the detection and analysis of Barkhausen noise bursts in various types of specimens. Existing Barkhausen noise detection apparatus was used. The specimens were plate specimens of AISI 4340 steel and AISI 4130 steel. Oscilloscope photographs were analyzed to determine the detailed characteristics of both the processed and unprocessed Barkhausen noise signals. For investigation of the statistical characteristics of Barkhausen noise, pulse counting and sorting methods were used, as well as real-time analysis of correlation functions, probability amplitude functions and probability distribution functions. These parameters were analyzed for specimens subjected to various applied stress fields, including uniaxial tension and cantilever bending, and for variation of parameters such as magnetization rate and probe liftoff.

The investigation showed that the Barkhausen noise signal often consists of two distinct parts which respond differently to stress. This observation applied to both the processed analog Barkhausen signature and results of pulse counting approaches. It was found that measuring the ratio of the amplitudes between two segments of the Barkhausen signal is a viable approach to stress measurement and could potentially provide an approach for overcoming the difficulties associated with parameters other than stress. Experiments on specimens stressed in uniaxial tension and cantilever bending showed that the shapes of the Barkhausen signals and the statistical characteristics depend on the mode of loading. Although further work is needed to clarify the results, these experiments suggest that analysis of the shape of the Barkhausen signal may provide a means for determining different stress configurations. Frequency spectrum analysis showed that although there are frequency components in the Barkhausen noise extending as high as 500 kilohertz, the dominant noise components are contained within the frequency range of 10 kilohertz to 100 kilohertz. The lower frequency components were found to change more drastically with stress than the higher frequency components.

Investigation of the autocorrelation function, amplitude probability density, and amplitude probability distribution of Barkhausen noise signals showed that these functions correspond closely to those obtained from random noise and are therefore indicative of the random nature of the Barkhausen phenomena. Data obtained as a function of cantilever bending stress for various magnetization rates and amounts of probe liftoff showed that, although the correlation function is not strongly sensitive to stress, it is more sensitive to stress than to magnetization rate or probe liftoff. Thus, analysis of the correlation function could be a viable approach to obtaining a stress indicator which is insensitive to magnetization rate and probe liftoff.

Based on these findings, an improved Barkhausen stress measuring instrument was developed and fabricated. The instrument contains a number of special features such as two adjustable gates for selecting portions of the Barkhausen signal for analysis, digital readout of either gate or the ratio of the gates, outputs for both the processed and unprocessed Barkhausen signals and a Hall-effect element in the probe for sensing and controlling the applied magnetic field. The instrument was tested and delivered to AMMRC in conformity with the contractual requirements.

Recommendations for further work include additional analysis of the statistical parameters, especially the correlation functions, as a basis for improved stress measurements. At the present time, one limitation to exploiting this approach is the lack of stress sensitivity exhibited by the correlation function. A cursory investigation was conducted directed toward analyzing only selected portions of the Barkhausen bursts, and selected frequency bandwidths, for increased sensitivity to stress, however, the results were inconclusive. Additional investigations of the relationship between the statistical parameters and the detailed characteristics of the stress field could be important as a potential means of distinguishing between various stress configurations.

II. EXPERIMENTAL PROCEDURE

For most of the investigation, two specimens of AISI 4340 steel and one specimen of AISI 4130 steel were used. The AISI 4340 steel specimens were numbered AA36 and AA41. These specimens were approximately 6-1/2 inches long, 1-1/2 inches wide and 1/8 inch thick. The AISI 4130 specimen was approximately 10 inches long, 1-1/2 inches wide and 0.111 inch thick.

The experiments were conducted using Barkhausen noise analysis methods discussed in Appendix A. A Kepco bipolar operational power amplifier was used to supply current to the magnet. The magnetizing frequencies utilized were in the range of 0.5 Hz to 5 Hz with magnetizing currents of up to ± 1 amp. The frequency response of the Barkhausen noise system was checked and found to be flat from approximately 1 kHz to 100 kHz. For pulse counting, a Nuclear Data 1024-channel pulse height analyzer was used. This device sorts and counts incoming pulses according to their amplitudes. In application to Barkhausen noise, the discriminator threshold on the pulse height analyzer was set just above the amplifier background noise level so only Barkhausen pulses above this level were counted. In addition to the pulse counting experiments, a number of experiments were performed using the multiscaling mode of operation on the pulse height analyzer. In this mode, the number of incoming pulses is counted regardless of the pulse amplitude, for a selected dwell time per channel. Thus, one obtains the distribution in number of pulses versus time, or in the case of Barkhausen noise, the distribution in pulse number along the burst.

The statistical characterization experiments were conducted using a Saicor 400-channel correlation analyzer. This instrument allows correlation functions, amplitude probability density, and amplitude probability distribution functions to be obtained in real-time. The advantage of a real-time approach is that rapid and immediate analysis of the results is available so that the influence of changing experimental parameters can be immediately assessed. Any required instrumentation adjustments can then be readily made. For most of the experiments, a sample increment time of 0.2 microseconds was utilized to obtain the greatest available resolution. A trigger pulse unit was fabricated to provide adjustable trigger pulses synchronized with the magnetizing current waveform. This device allowed the correlation analyzer (and other instrumentation) to be synchronized with any point during the Barkhausen bursts. The total analysis time of the correlation analyzer could be adjusted to obtain either a certain portion of the burst or the entire burst.

Power spectral density results were obtained by utilizing a Biomation transient recorder in conjunction with the correlator and a spectrum analyzer. The correlator was used to obtain the autocorrelation function of the Barkhausen noise which was then digitized and recorded by the Biomation instrument. The output of the Biomation recorder was repetitively fed into the spectrum analyzer to obtain the power spectrum. Results of the procedure were verified by comparison with those obtained by direct frequency spectrum analysis.

The stress experiments were conducted utilizing both cantilever bending stress and uniaxial tensile stress. The cantilever bending test fixture is shown in Figure 1. Data could be obtained for both tensile and compressive cantilever bending stress using this fixture. The stress in the specimen was determined by measuring the deflection of the edge and using the specimen dimensions to compute the stress at the location of the Barkhausen probe. The uniaxial stressing fixture which was made entirely of nonmagnetic alloys is shown in Figure 2. This device is equipped with a calibrated load cell whose strain gage output can be read on a standard readout instrument. However, for the experiments reported here, strain gages were mounted on the specimen and used to measure strain directly during axial loading.

In the experiments performed, the AISI 4340 steel specimens could be stressed only in the cantilever bending stressing fixture; however, the AISI 4130 specimen was stressed both in the cantilever bending stressing fixture and the uniaxial stressing fixture. The maximum stresses applied were 50 ksi which is well below the yield stress for all of the specimens investigated.

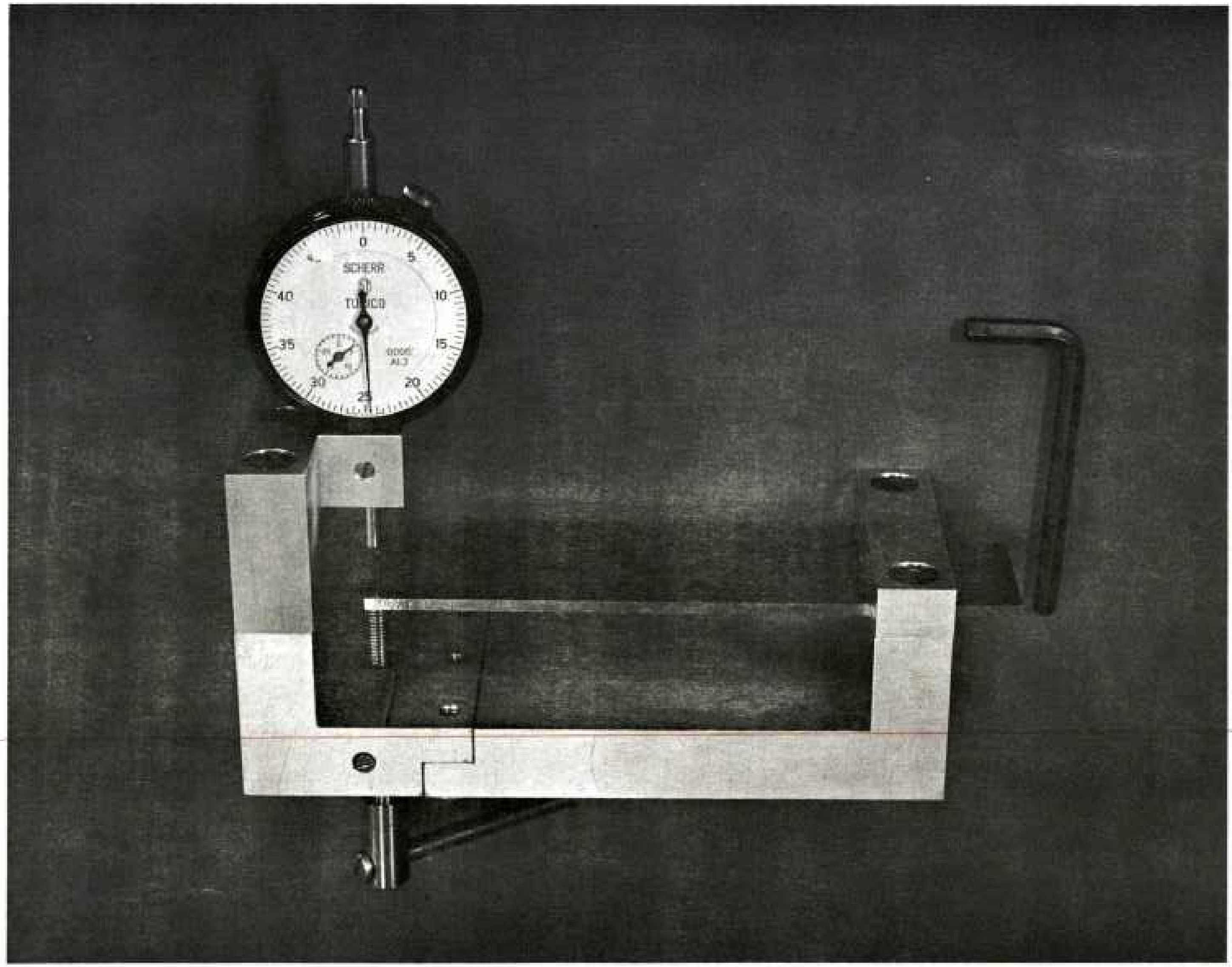

FIGURE 1. CANTILEVER BEAM LOADING FIXTURE WITH DIAL MICROMETER

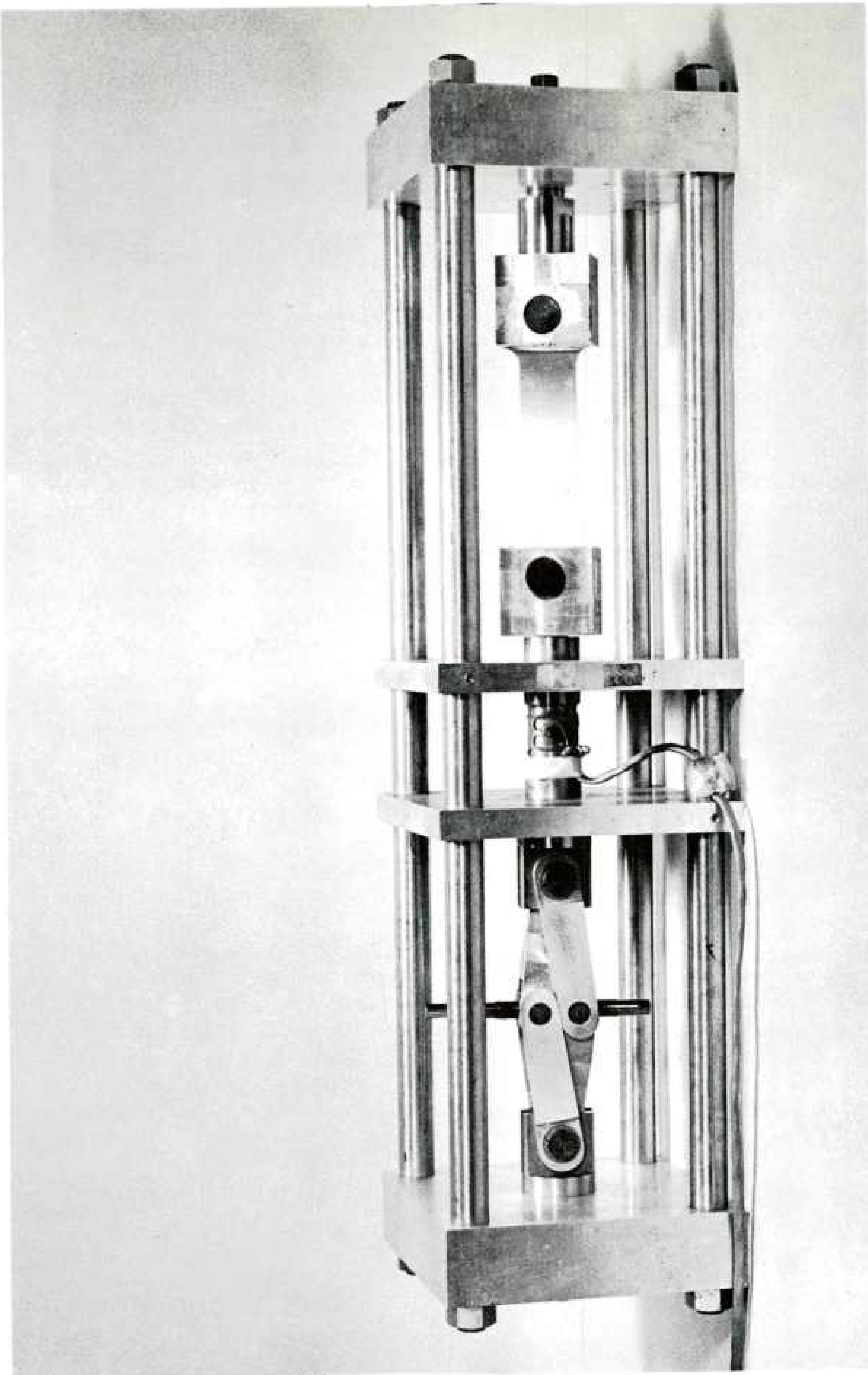

FIGURE 2. NONMAGNETIC UNIAXIAL STATIC STRESS FIXTURE.

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III. RESULTS AND DISCUSSION

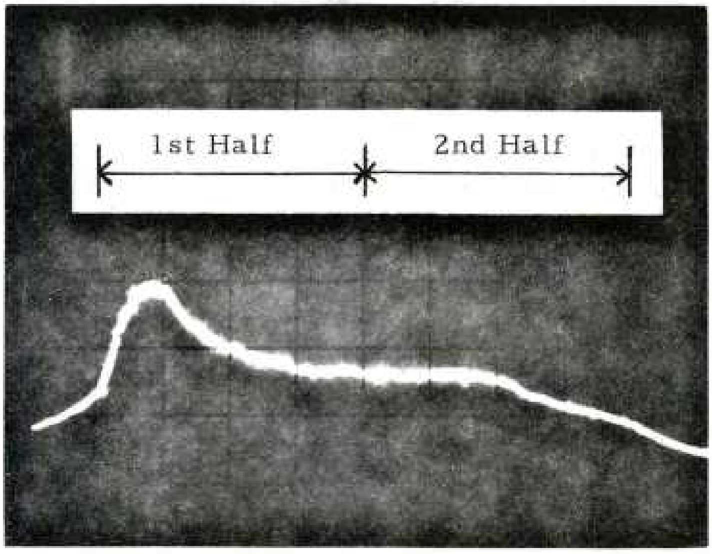
A. General Characteristics of Barkhausen Noise

To investigate the characteristics of Barkhausen noise pulse trains, oscilloscope photographs were taken of Barkhausen noise at four temporal locations during the burst. The adjustable synchronizing unit described in the previous section was used to trigger the oscilloscope trace at specified times during the burst. The photographs were made on a sufficiently expanded time scale (5 μsec/cm) so that the individual pulses of the noise could be resolved. Data were taken on specimen AA36 as a function of both tensile and compressive cantilever bending stress. Examination of the photographs showed that, on the specimen investigated, the general characteristics of the Barkhausen noise are uniform throughout the burst, and increasing tensile stress tends to primarily increase the low frequency contributions to the noise.

In addition to investigating the general characteristics of the Barkhausen noise at various locations during the burst, an analysis was carried out of the entire Barkhausen burst by taking oscilloscope photographs of both the unprocessed noise and the signatures obtained by amplitude-detecting the envelope of the noise burst. These data were taken on AISI 4340 steel specimens AA36 and AA41 as a function of cantilever bending stress. The trigger synchronizing circuit was used to ensure that the oscilloscope triggered each time at the same point relative to the Barkhausen burst. In general, for the two specimens investigated, it was found that the Barkhausen signature consisted of two distinct parts as shown in Figure 3. The first half tended to change noticeably with stress whereas the second half remained almost constant. Plotting peak voltage measurements of the two halves showed that the ratio of the two peaks varied with stress in the same way as the first peak alone. Thus, the <u>ratio</u> of the two peaks may be a candidate method as an indicator of stress instead of the <u>amplitude</u> of the first peak. The general applicability of this approach for stress measurement requires further exploration. If it is found that both halves of the signal are affected in the same way by probe liftoff and magnetization changes, then the ratio approach to stress measurement might afford a means of circumventing the detrimental influence of these former parameters.

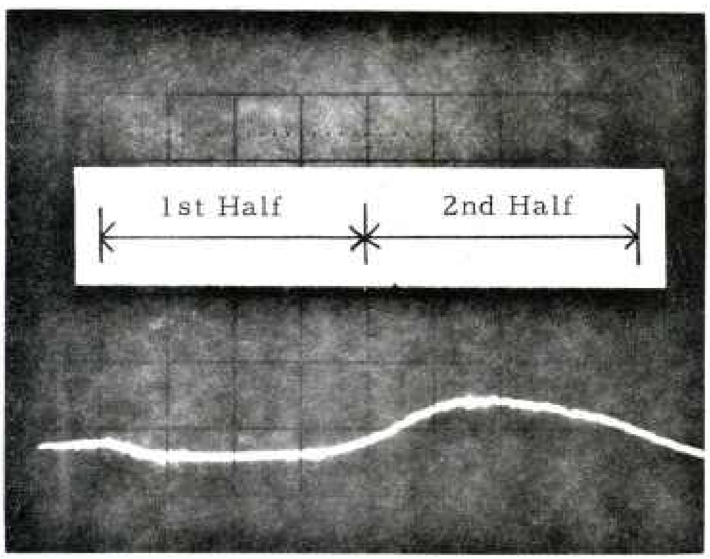
B. Pulse Analysis

Examples of pulse amplitude spectra obtained at a magnetizing current rate of 0.4 amp/sec for a counting time of two minutes are shown in Figure 4a. Although the total count number, N_T, is essentially



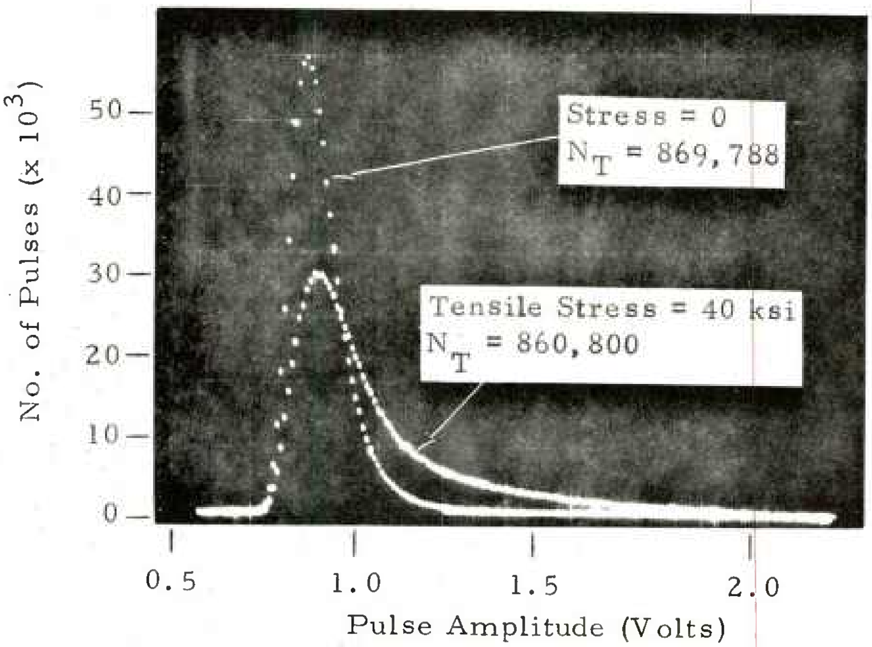
0 Applied Stress
0.5 v/div
50 msec/div

3823



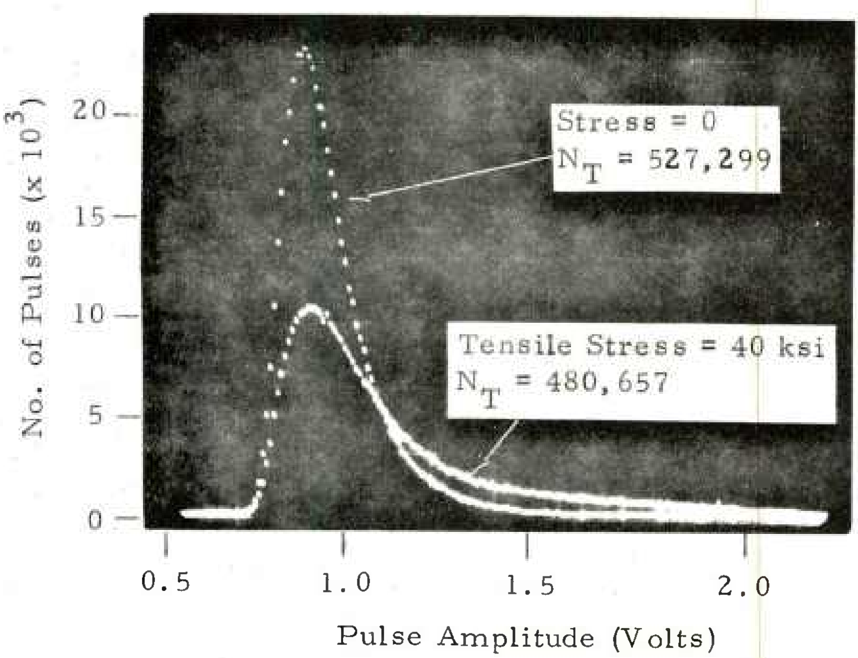
50 ksi Compression
0.5 v/div
50 msec/div

FIGURE 3. PROCESSED BARKHAUSEN SIGNATURE FROM SPECIMEN AA36 (AISI 4340)



a. Magnetizing Current Rate = 0.4 amp/sec

3655

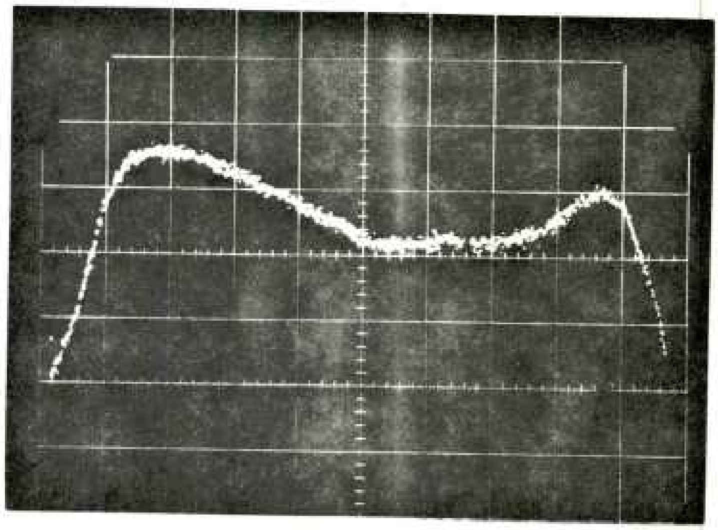


b. Magnetizing Current Rate = 0.8 amp/sec

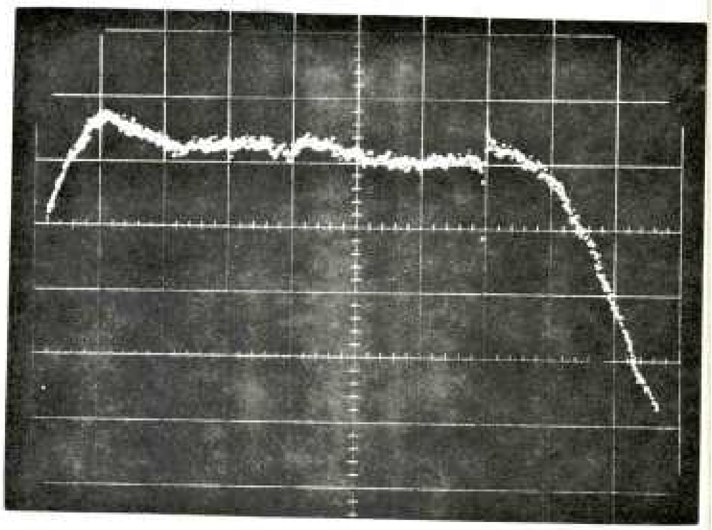
FIGURE 4. AMPLITUDE SPECTRA OF BARKHAUSEN PULSES IN AISI 4340 STEEL

the same for zero stress as for a tensile stress of 40 ksi, the shapes of the spectra are quite different. For example, for the case of tensile stress, the number of large amplitude pulses increases relative to that for zero stress, while the number of small amplitude pulses decreases. This implies that the increase in amplitude of the processed Barkhausen signal with tensile stress, which is usually observed[4], may be due primarily to an increase in the number of large amplitude pulses rather than an overall increase in the total number of pulses. For comparison, similar spectra obtained for a magnetizing current rate of 0.8 amp/sec and a counting time of 1 minute (providing the same number of Barkhausen bursts as the magnetizing current rate of 0.4 amp/sec) are shown in Figure 4b. Although the relative changes in the spectra with stress are similar to those shown in Figure 4a, comparison of Figures 4a and 4b shows that the shape of the spectra are dependent upon magnetization rate. For example, in Figure 4b, the ratio of large amplitude pulses to small amplitude pulses is increased relative to that indicated in Figure 4a for comparable stress conditions. These results suggest that analysis of the pulse amplitude spectra could provide a means for compensating Barkhausen noise measurements for effects of magnetization rate changes. However, utilization of this approach in a practical stress measuring instrument would entail an extensive electronics development effort.

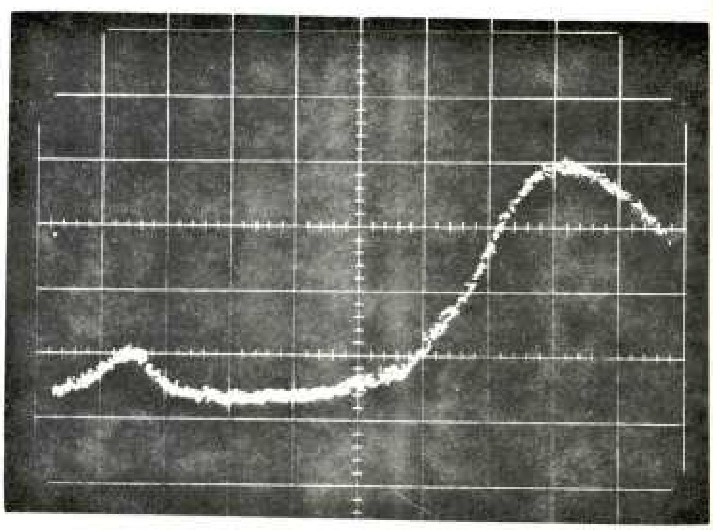
A number of experiments were performed using the multiscaling mode of operation on the pulse height analyzer. The results for specimen AA41 are shown in Figure 5 for several conditions of applied stress. Note that for tensile stress, the number of pulses increases at the beginning of the burst and then becomes practically constant until decreasing sooner than for the case of zero applied stress. On the other hand, for compression, the pulse number is drastically reduced during the first half of the burst while remaining almost as high during the latter part of the burst as for the case of zero applied stress. These results were further explored by performing multiscaling experiments on the two halves of the Barkhausen burst individually as a function of stress. The total number of pulses occurring during each half of the burst were determined and the results are shown graphically in Figures 6 and 7. As can be seen, for both specimens, the pulse number during the first half of the burst increases slightly with tensile stress while decreasing rapidly with compressive stress. On the other hand, the pulse number during the second half remains relatively high even in compression, and for specimen AA36 shows a steady decline with compressive stress. These results indicate that more responsive indications of tensile and compressive stresses might be obtained by measuring the changes in pulse number during selected portions of the Barkhausen burst.



0 Applied Stress



40 ksi Tension



40 ksi Compression

3824

FIGURE 5. PULSE NUMBER DISTRIBUTION DURING BARKHAUSEN BURST IN AISI 4340, SPECIMEN AA41

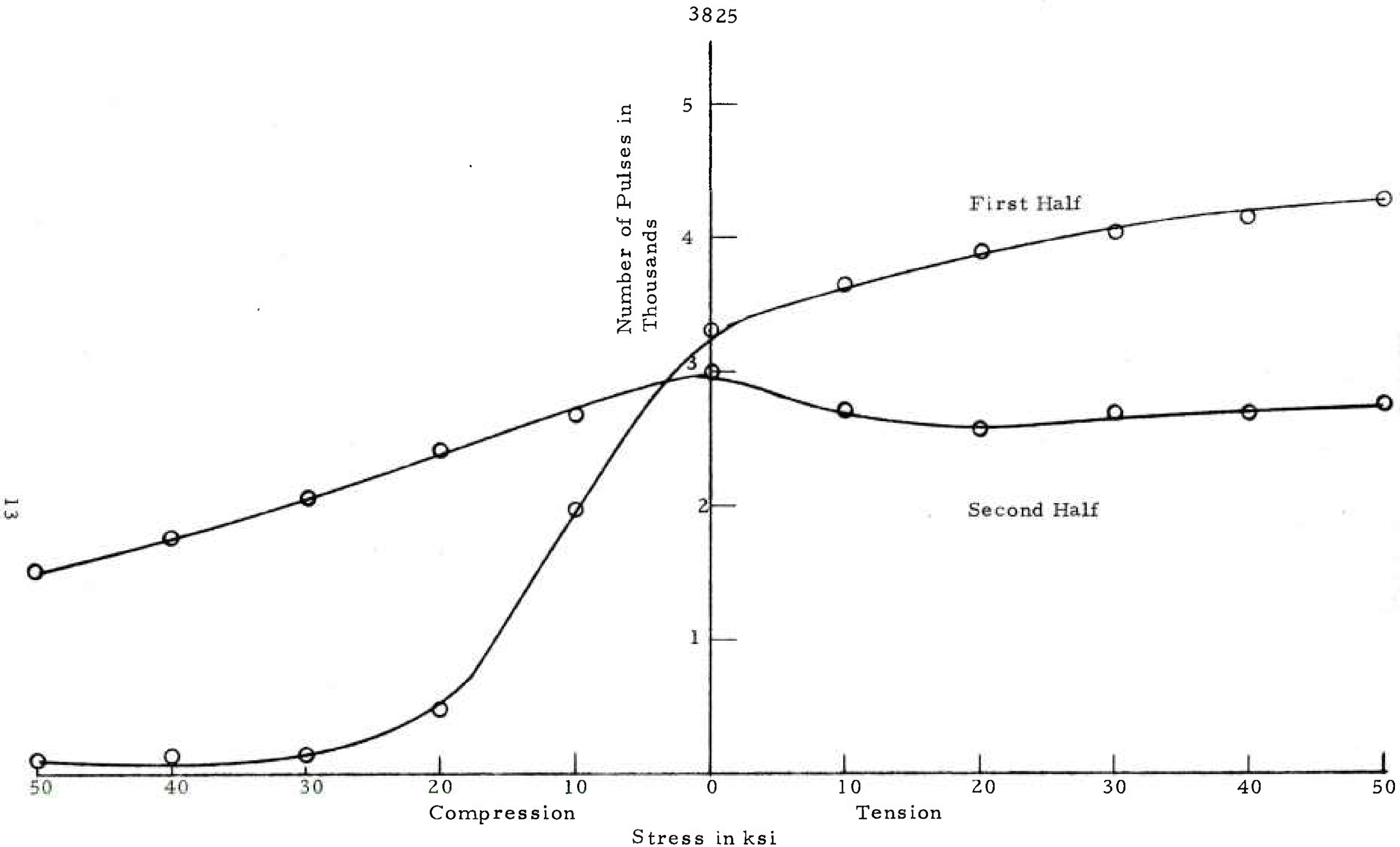


FIGURE 6. BARKHAUSEN PULSE TOTALS DURING FIRST AND SECOND HALVES OF THE BURST. SPECIMEN AA36.

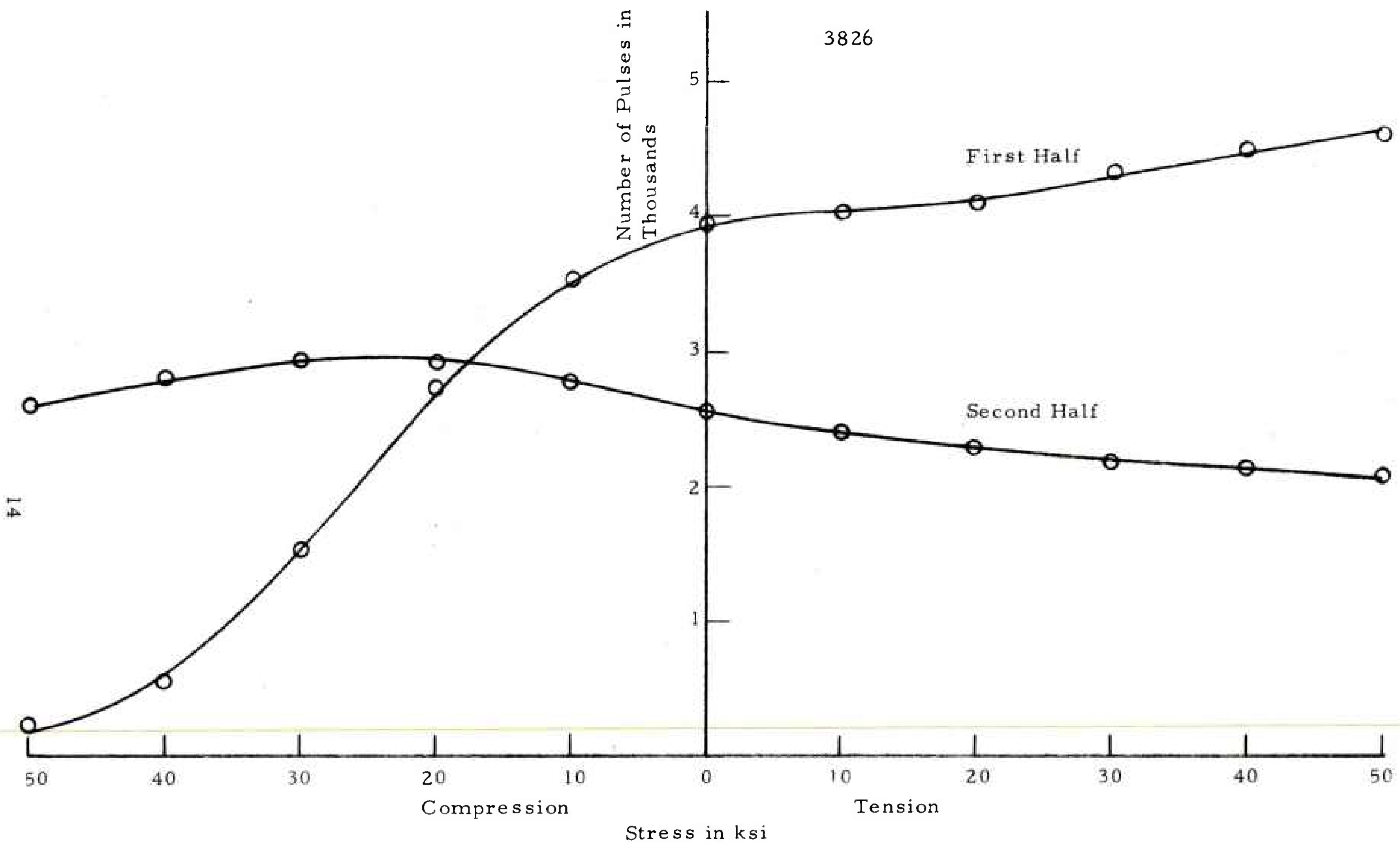


FIGURE 7. BARKHAUSEN PULSE TOTALS DURING FIRST AND SECOND HALVES OF THE BURST. SPECIMEN AA41.

C. Statistical Characteristics of Barkhausen Noise

Shown in Figure 8 are examples of a typical autocorrelation function, amplitude probability density, and amplitude probability distribution of Barkhausen noise. These functions correspond closely with those obtained from white noise and are therefore indicative of the random nature of the Barkhausen phenomena. Autocorrelation functions were obtained as a function of cantilever bending stress for various magnetization rates and amounts of probe liftoff. Listed in Table I is the width of the correlation function at half amplitude for different condtions. The results indicate that although the correlation function is not strongly sensitive to stress, it is more sensitive to stress than to magnetization rate or probe liftoff. The change in correlation function with probe liftoff for compression is not entirely understood at this time, but may be due to the decreased Barkhausen signal amplitude associated with compressive stress.

As the results in Table I indicate, analysis of the correlation function could be a viable approach to obtaining a stress indicator which is insensitive to magnetization rate and possibly also to probe liftoff. However, it would be desirable to have comparable sensitivity to stress as the presently used method which involves a measurement of the amplitude of the Barkhausen noise envelope[4]. For this reason, operating conditions other than those shown in Table I were investigated with the hope of finding conditions for which the Barkhausen noise correlation function exhibited increased sensitivity to stress. Operating conditions investigated included analyzing only selected portions of the Barkhausen burst and selected frequency bandwidths. No increased sensitivity to stress was observed by examining selected portions of the Barkhausen burst, but using selected frequency bandwidths may hold promise. Autocorrelation functions obtained for bandwidths of 1 kHz to 100 kHz and 1 kHz to 50 kHz are shown in Figure 9. Note that reducing the bandwidth introduces oscillations into the correlation function (compare with Figure 8). A cursory analysis showed that the shape of the oscillating function is slightly dependent upon stress (probably due to the changes in frequency spectrum associated with stress). Thus, appropriate selection of bandwidth and comparative analysis of the correlation function zero crossings may provide an acceptable stress measuring approach. As in the case of pulse height analysis, however, the development of electronic processing instrumentation for practical application was outside the scope of the present program.

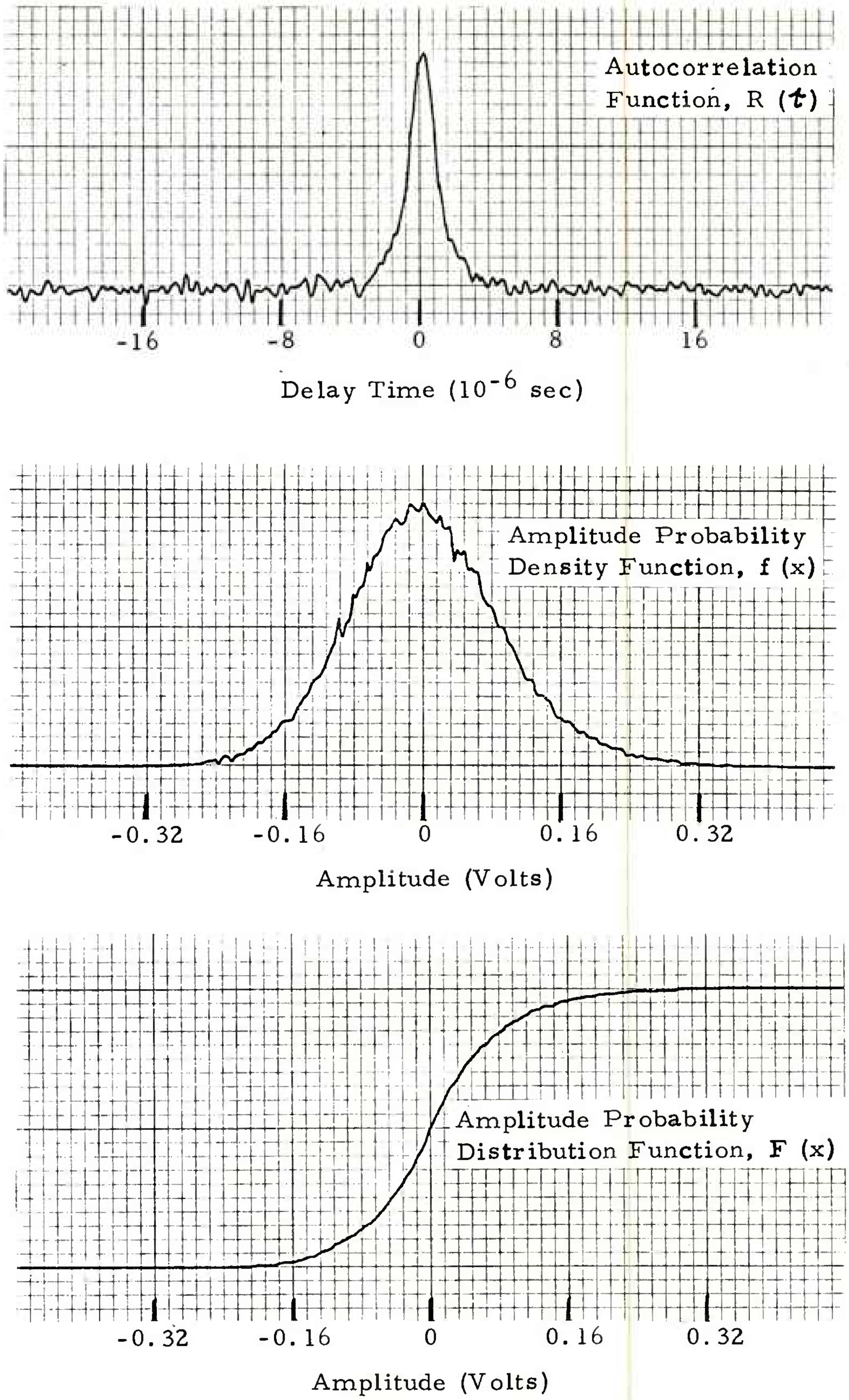


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FIGURE 8. CORRELATION AND PROBABILITY FUNCTIONS OF BARKHAUSEN NOISE FROM AISI 4340 STEEL

TABLE I

WIDTH OF AUTOCORRELATION FUNCTION AT HALF-AMPLITUDE FOR SPECIMEN AA36 (AISI 4340)

(Bandwidth 200 Hz to 3 MHz; sample increment 0.2 μsec.)

Magnetizing Current Rate (Liftoff = 0)	Stress		
	0	50 ksi tension	50 ksi compression
0.2 amp/sec	1.0 μs	1.9 μs	0.7 μs
0.4 amp/sec	1.0	2.0	0.8
0.8 amp/sec	1.0	1.9	0.7
Probe Liftoff (Magnetizing Current Rate = 0.4 amp/sec)			
0	1.0	2.0	0.8
0.016 in.	1.0	2.0	0.4
0.032 in.	1.0	1.9	0.5

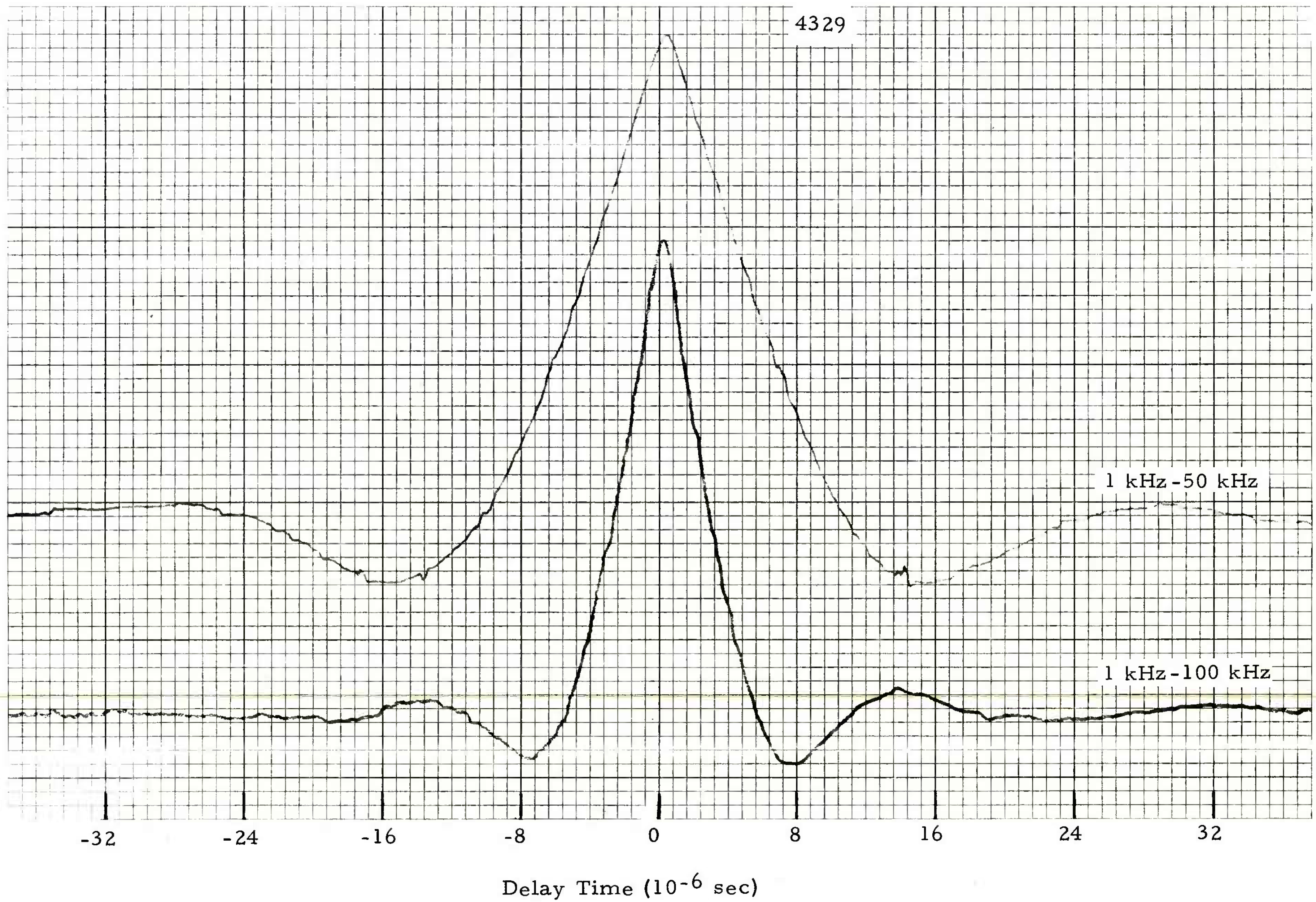


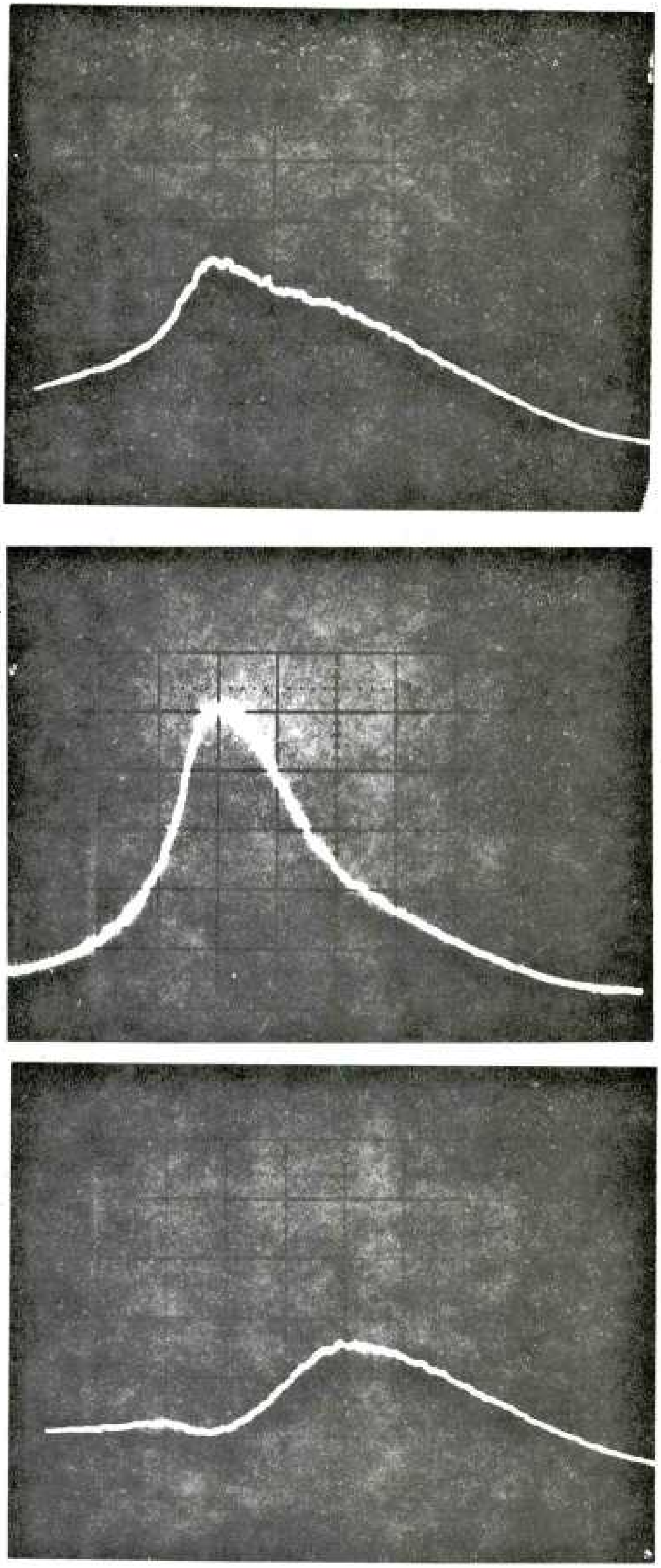
FIGURE 9. BARKHAUSEN NOISE AUTOCORRELATION FUNCTIONS FOR VARIOUS BANDWIDTHS

D. Comparison Between Cantilever Bending Stress and Uniaxial Tensile Stress

An investigation was conducted using a flat tensile specimen of AISI 4130 steel which could be loaded in both uniaxial tension and cantilever bending in order to compare results for these two different stress modes. In general, it was found that the Barkhausen signals differed noticeably, depending on whether the applied stress was uniaxial or cantilever bending. Figure 10 shows the amplitude-detected Barkhausen signal envelopes for cantilever bending tensile and compressive stress of 30 ksi; Figure 11 shows the results for uniaxial tensile stress of 30 ksi. As can be seen, for the uniaxial case, application of tensile stress produces a pronounced double peak whereas only a single peak is observed for cantilever bending tensile stress. Also, in the case of cantilever bending, primarily the first half of the signal is affected by stress whereas the entire signal is modified by uniaxial tension. The differences between the results for the two cases may be associated with the different stress fields that exist, that is, relatively uniform stress for uniaxial loading and a stress gradient through the specimen for cantilever bending. These results suggest that analysis of the shape of the Barkhausen signature may potentially provide an approach for distinguishing between different stress conditions.

A plot of the peak Barkhausen signal amplitude versus stress is shown in Figure 12 where the two halves of the uniaxial stress signature are individually plotted. As is seen, for cantilever bending, a smooth S-shaped curve is obtained from compression through tension similar to the results reported in a number of previous investigations[8]. In uniaxial tension, the two peaks of the signature behave slightly differently with stress, but generally show an increase in amplitude with increasing stress.

Differences between uniaxial stress and cantilever bending were also observed for the statistical parameters. Figure 13 illustrates the probability density functions obtained for the two stress conditions for a stress level of 40 ksi. For cantilever bending, the probability density at zero amplitude increases with both tensile and compressive stress, whereas, for uniaxial tension, the probability density decreases at zero amplitude but increases for larger amplitudes. The amplitude probability distributions were found to behave similarly to the probability density functions with regard to the different stress conditions; however, the autocorrelation functions were found to be affected very little by stress for either mode of application.



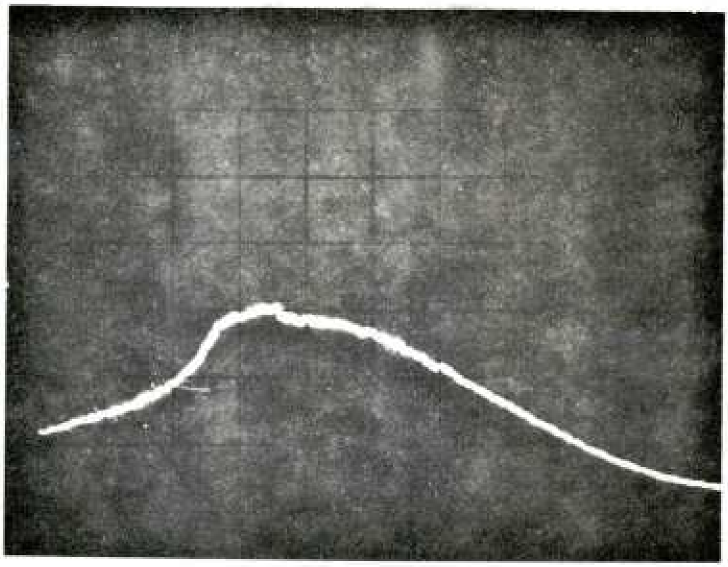
0. 5V/div
50 msec/div
0 Stress

0. 5V/div
50 msec/div
Tensile Stress = 30 ksi

0. 5V/div
50 msec/div
Compressive Stress = 30 ksi

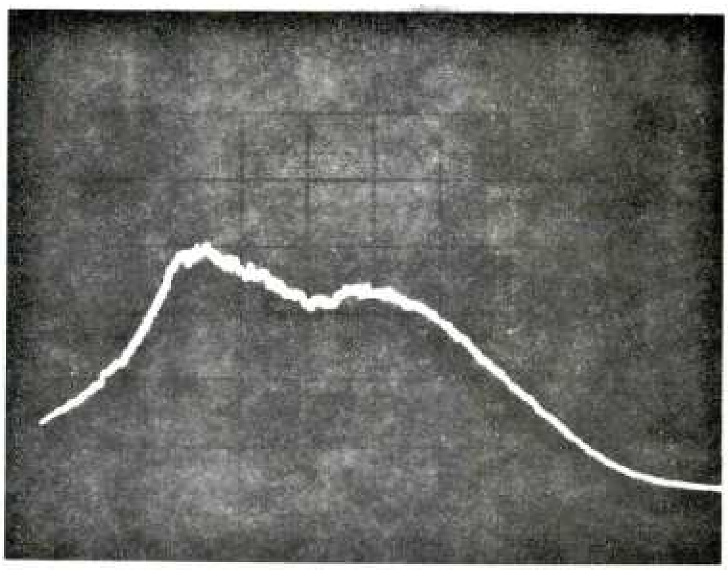
4327

FIGURE 10. PROCESSED BARKHAUSEN NOISE SIGNATURES FOR CANTILEVER BENDING STRESS



0.5V/div
50 msec/div
0 Stress

4328



0.5V/div
50 msec/div
Tensile Stress = 30 ksi

FIGURE 11. PROCESSED BARKHAUSEN SIGNATURES FOR UNIAXIAL TENSILE STRESS

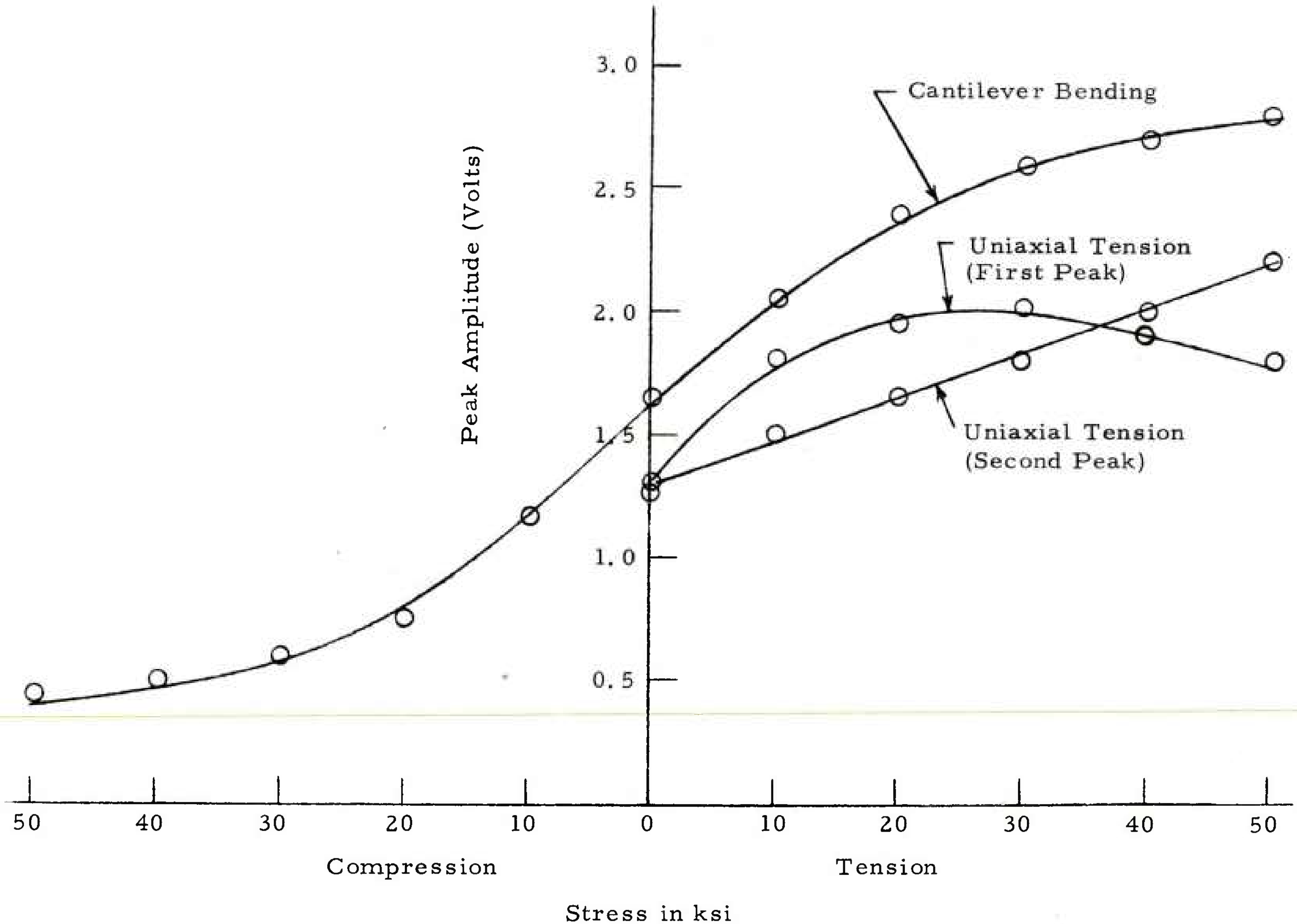
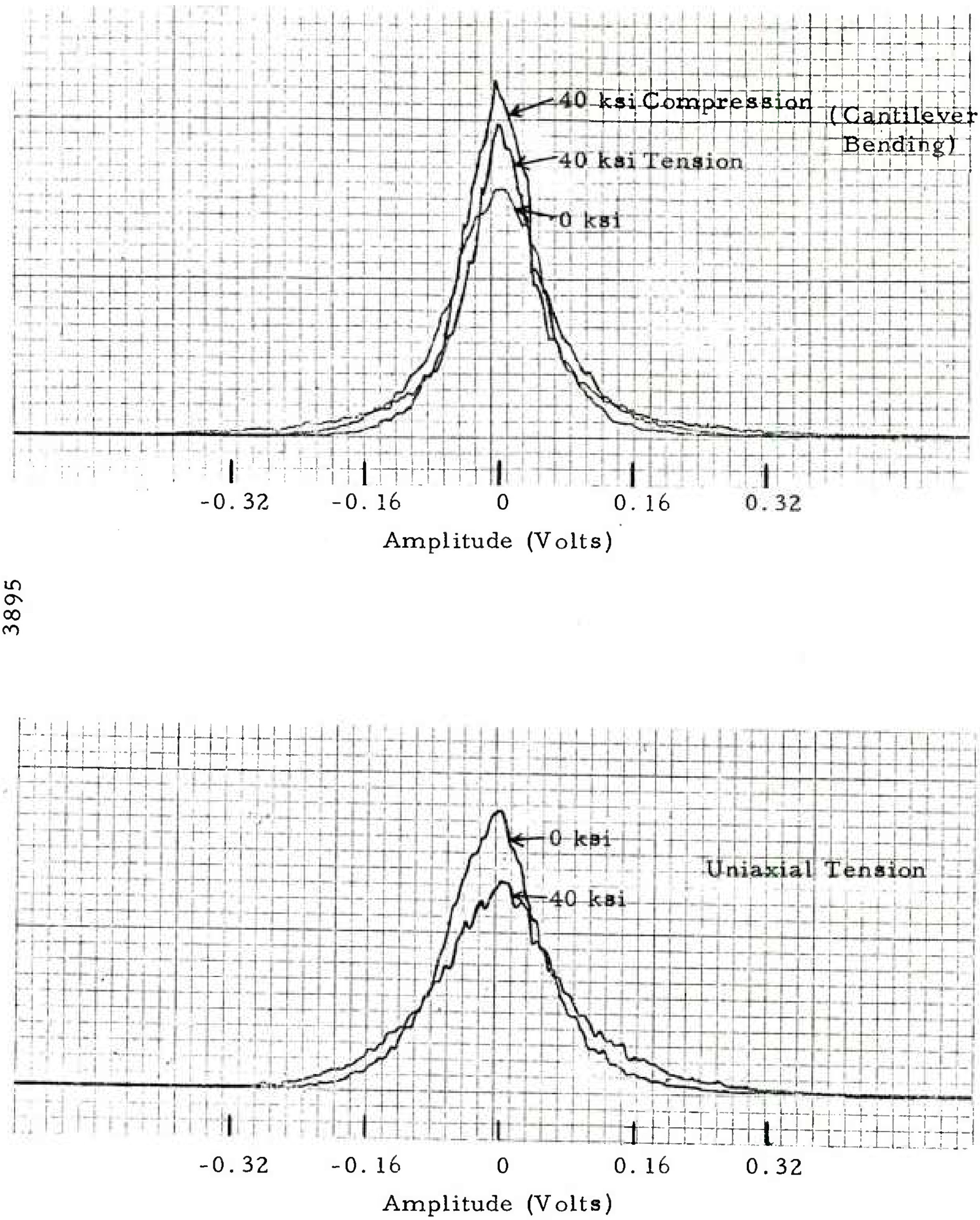


FIGURE 12. BARKHAUSEN SIGNAL PEAK AMPLITUDE VS. STRESS



3895

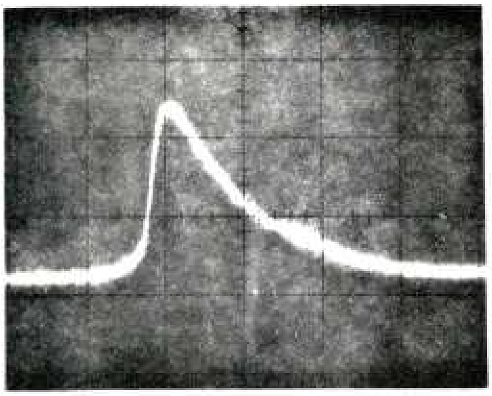
FIGURE 13. BARKHAUSEN NOISE PROBABILITY DENSITY FUNCTIONS FOR A SPECIMEN OF AISI 4130 STEEL

E. Characteristics of New Barkhausen Stress-Measuring Instrument

Based on the results of the foregoing investigation, a Barkhausen Noise Stress Measurement System was developed, fabricated, and delivered to the U.S. Army Materials and Mechanics Research Center. To provide desired flexibility for stress measurement, the new Barkhausen instrument possesses a number of special features, such as, adjustable gates for selecting portions of the Barkhausen signal for analysis; outputs for both the processed and unprocessed Barkhausen signals; and a Hall-effect element in the probe for sensing and controlling the magnetic field. In addition, the instrument has controls for varying the magnetizing current rate and amplitude; outputs for the sweep voltage, magnetizing current, and Hall-effect voltage; and a monitor oscilloscope. Additional details can be found in Appendix B.

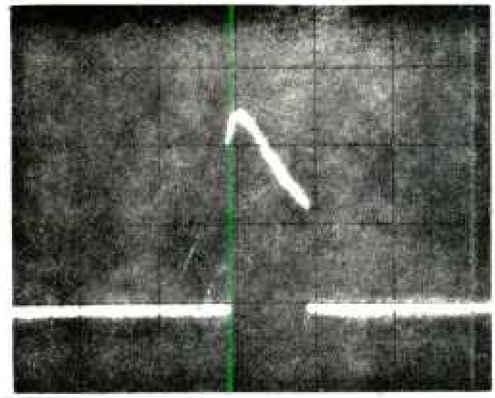
Oscilloscope traces of some of the signals obtained with the Barkhausen Noise Stress Measurement System are illustrated in Figure 14. In Figure 14a is shown a typical processed Barkhausen signature obtained from an AISI 4340 steel specimen. In Figure 14b, a gated portion of the same signature is shown. Two gates are available; each is variable in width and location. A digital readout provides the maximum amplitude appearing in either gate or the ratio of the maximum amplitudes in the two gates. With the gate feature, selected portions of the Barkhausen signal may be analyzed and compared providing useful information regarding stress as discussed in previous sections. Figure 14c shows the Hall-effect element output without magnetic feedback. This is essentially a measure of the magnetizing force at the surface of the specimen. Note the nonlinearity at the zero-crossing caused by demagnetizing effects. Figure 14d shows the Hall-effect element output with magnetic field change to be retained as the specimen geometry, and other conditions which affect the applied field, are varied.

The Barkhausen Noise Stress Measurement System developed during this program provides considerable flexibility for the measurement of stress enabling it to be adapted to a variety of applications. In most cases, the specific measurement approach used will depend on the application and on the desired results. In general, the instrument is suitable for both laboratory and field measurements.



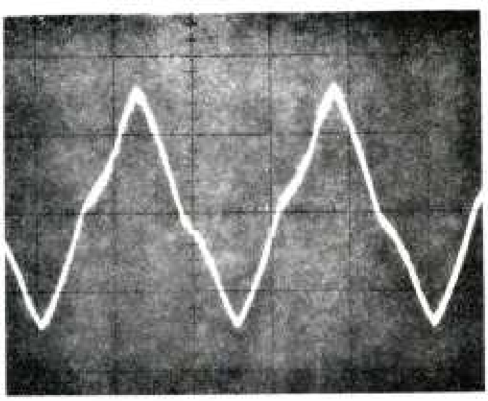
a. Processed Barkhausen Signature from AISI 4340 Steel

V: 0.2 V/div
H: 50 msec/div



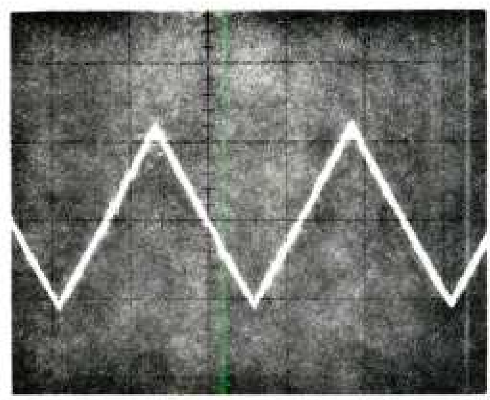
b. Gated Barkhausen Signature from AISI 4340 Steel

4150



c. Hall Element Output - No Magnetic Feedback

V: 0.2 V/div
H: 0.5 sec/div



d. Hall Element Output - With Magnetic Feedback

FIGURE 14. TYPICAL SIGNALS OBTAINED WITH BARKHAUSEN NOISE INSTRUMENTATION SYSTEM

IV. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached as a result of the Barkhausen noise investigation program:

1. The autocorrelation function, amplitude probability distribution and probability density function of the unprocessed Barkhausen noise correspond with the comparable statistical functions for random noise. This result may be associated with the broad-band characteristics of the Barkhausen noise phenomenon and the detection instrumentation.

2. The Barkhausen noise autocorrelation function is independent of magnetizing current rate and is only slightly dependent on stress in the broad-band mode. Reducing the detection bandwidth for the correlation function may lead to increased sensitivity to stress.

3. In some cases, the Barkhausen signal is composed of two or more distinct parts which respond differently to stress. This result was corroborated by multiscaling and pulse counting experiments.

4. The capability for measuring selected portions of the Barkhausen signal provides flexibility in adapting the Barkhausen stress measurement method to specific applications.

5. Barkhausen noise pulse height spectra respond differently to stress and magnetizing current rate changes potentially providing an approach for separating these two effects.

6. Several Barkhausen noise parameters, including statistical parameters, behave differently depending on whether the applied stress is uniaxial or cantilever bending. Thus, with appropriate auxiliary signal processing it may be possible to use Barkhausen noise to obtain information on stress configurations and gradients.

The following recommendations are made as a result of the Barkhausen noise investigation program:

1. Further explore the detailed statistical characteristics of Barkhausen noise with a view toward developing an approach which enhances the sensitivity of the statistical parameters to stress. Included in potential avenues is the use of cross-correlation techniques.

2. Further explore the feasibility of utilizing pulse height analysis and pulse counting for Barkhausen noise stress measurement.

3. Investigate the relationship between various characteristics of Barkhausen noise and the mode of applied stress as a potential means of utilizing Barkhausen noise to determine stress configuration and gradients.

4. Determine the effect of plastic deformation on the statistical characteristics of Barkhausen noise and compare with results obtained for elastic stress.

5. Develop analytical models for explaining the influence of stress and metallurgical features on Barkhausen noise.

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APPENDIX A

BARKHAUSEN NOISE ANALYSIS

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BARKHAUSEN NOISE ANALYSIS

The Barkhausen effect is associated with the abrupt, discontinuous movements of magnetic domain walls as the magnetization of a ferromagnetic material is changed(A1). In applications, the domain arrangement is usually altered by a controlled time-rate-of-change of an externally applied magnetic field. The discrete changes in the specimen magnetization can be detected by means of voltage pulses induced in a coil placed in proximity to the specimen as shown in Figure A1. The voltage pulses are found to be random in amplitude, duration, and temporal separation, and may be described as "noise"; hence the term Barkhausen Noise. Figure A2 shows an example of Barkhausen pulses sensed by an induction coil near the surface of a low carbon steel bar.

The size,shape, and arrangement of the domains in a bulk ferromagnetic specimen, and thus the detailed dynamics of domain wall motion, are strongly influenced by various parameters of the specimen, in particular the state of mechanical stress(A2). Figure A3 shows several photographs of magnetic domains (made visible by a magnetooptic method) on the surface of a single crystal of silicon iron and illustrates the manner in which domains change under the influence of an applied stress(A3). A compressive stress was applied to the specimen from left to right in the illustration. A careful examination of these photographs shows marked changes occurring as the compressive stress is increased; for example, in the top photograph, the domains are principally oriented approximately 45 degrees upward and to the left, while in the bottom photograph, several domains have grown in a direction oriented upward and to the right.

In general, two approaches are available for processing Barkhausen information: analog methods, where a signal is obtained proportional to the envelope of a train of Barkhausen pulses, or digital methods, where the individual pulses are sorted and counted usually by means of a multi-channel pulse height analyzer. Thus far, in applications of the Barkhausen Noise method to stress measurement, the analog approach has generally been used, resulting in a typical signature for a reversal of the specimen magnetization as shown in Figure A4.

The peak amplitude of the Barkhausen signal obtained during a reversal of the specimen mangetization has been empirically found to provide a good qualitative and, under favorable conditions, quantitative indication of residual stress. For appropriate probe orientation, high peak amplitudes are obtained when the specimen is in tension, intermediate amplitudes are obtained from stress-free specimens, and low amplitude signatures are obtained when the specimen is in compression(A4).

1959

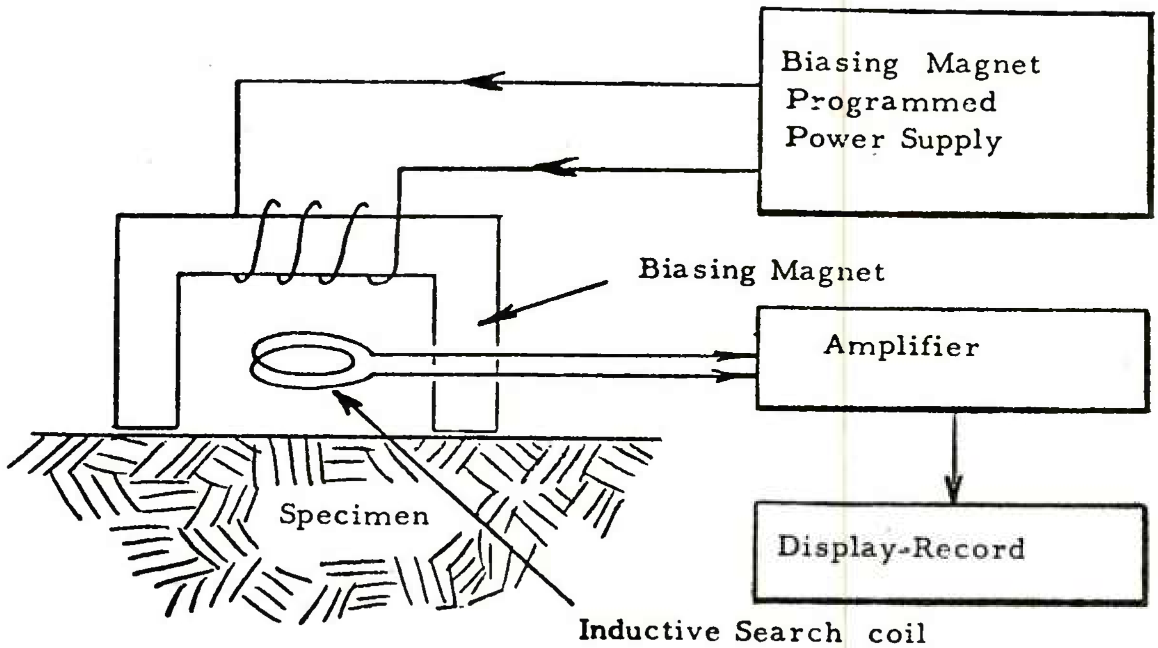
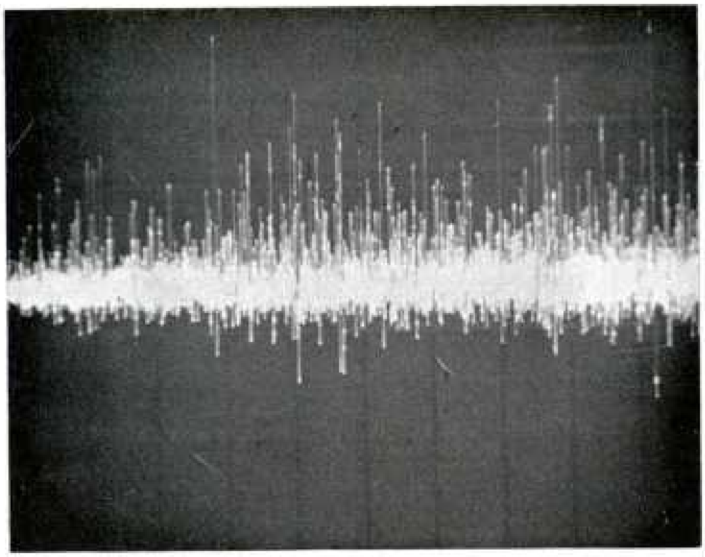


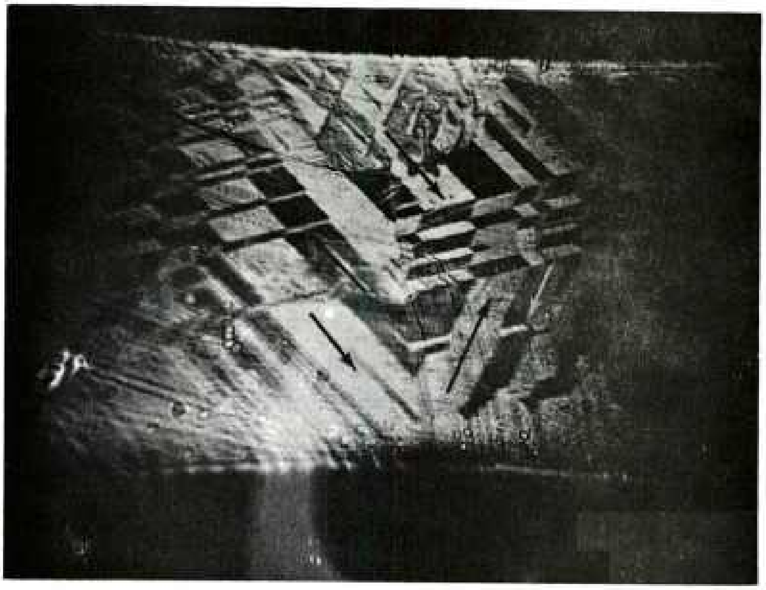
FIGURE A1. SCHEMATIC DIAGRAM OF THE ESSENTIAL FEATURES OF AN ARRANGEMENT FOR INDUCTIVELY SENSING THE BARKHAUSEN EFFECT

3140

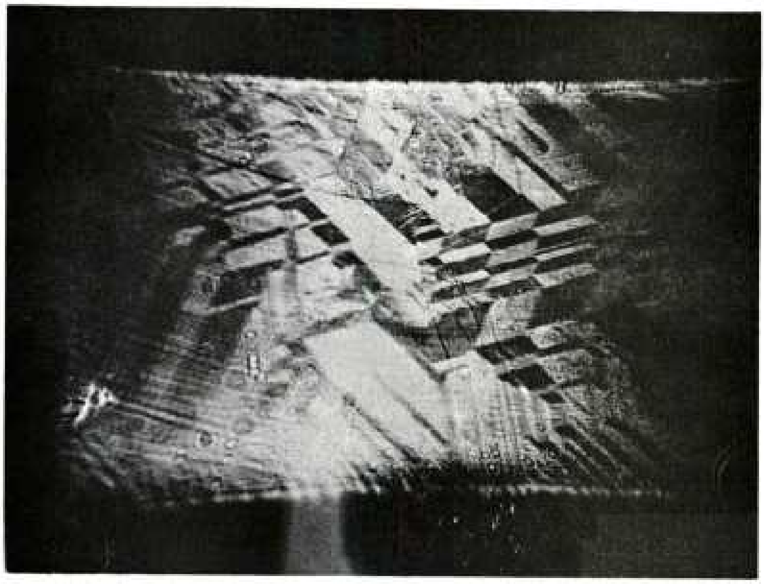


10 mv/cm vertical sensitivity
1 msec/cm sweep rate (horizontal)

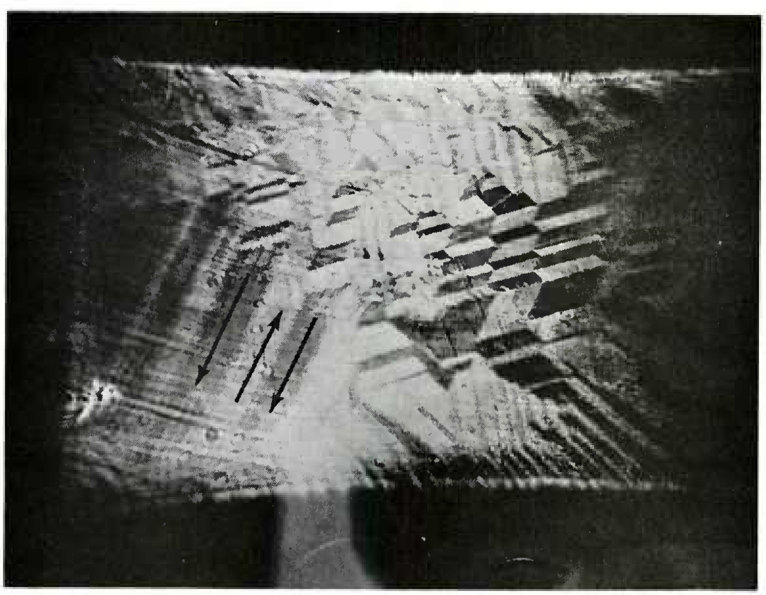
FIGURE A2. BARKHAUSEN NOISE PULSES



Compressive stress
of 900 psi



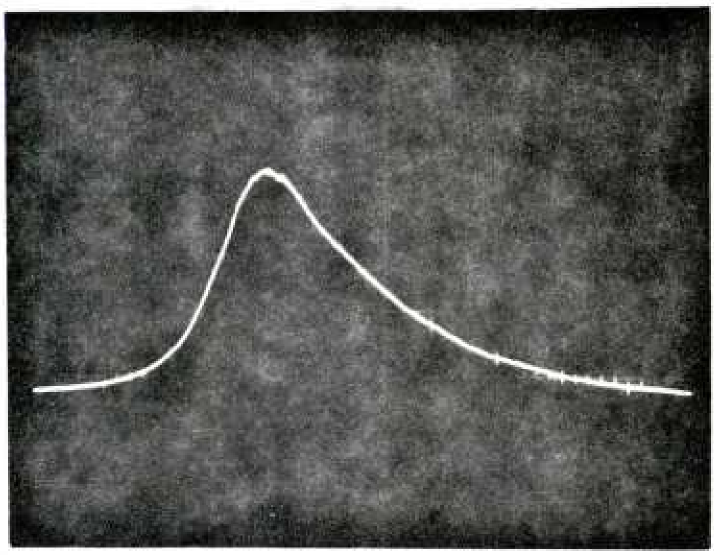
Compressive stress
of 1700 psi



Compressive stress
of 2600 psi

2291 b

FIGURE A3. INFLUENCE OF STRESS ON MAGNETIC DOMAINS IN SiFe SINGLE CRYSTAL SPECIMEN



4203

Hor: 50 msec/div

Vert: 0.1V/div

FIGURE A4. OSCILLOSCOPE DISPLAY OF A TYPICAL BARKHAUSEN SIGNAL ENVELOPE

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A4. Birdwell, J. A. and Barton, J. R., "Development and Application of Barkhausen Instrumentation Concepts for Measuring Stress in Ferromagnetic Steels," Final Report, Contract No. N00156-71-C-0362, Naval Air Engineering Center, Philadelphia, Pennsylvania, September 1971. Unpublished.

APPENDIX B

BARKHAUSEN NOISE STRESS MEASUREMENT SYSTEM

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BARKHAUSEN NOISE STRESS MEASUREMENT SYSTEM

The Barkhausen Noise Stress Measurement System was designed, developed and built at Southwest Research Institute. The purpose of this instrument is to indicate, qualitatively, the state of stress in ferromagnetic materials. The theory of operation is based on measurement of a magnetic signal as the specimen is magnetized. In operation, the specimen is magnetized by means of an applied time-varying magnetic field and the magnetic signal is detected by means of a small induction coil located at the surface of the specimen. The detected signal consists of a sequence of voltage pulses of random amplitude, duration, and separation called "Barkhausen Noise". The influence of stress on the Barkhausen Noise signal is used to obtain a qualitative indication of the state of stress in the specimen.

A photograph of the Barkhausen Noise Stress Measurement System is shown in Figure B1 and a simplified block diagram is given in Figure B2. A hand-held probe, connected to the Barkhausen instrumentation system by means of a cable, contains a C-shaped electromagnet for applying a time-varying mangetic field to the specimen, and the Barkhausen Noise detection coil. Also included in the probe are the 1st stage Barkhausen Noise preamplifier and a Hall effect magnetic field detector for monitoring the applied magnetic field at the surface of the specimen. The voltage from the Hall sensor is used in a magnetic feedback arrangement to provide control of the magnetic field variation applied to the specimen. In the feedback mode, the magnetic field at the specimen surface is forced to follow a reference waveform, either internally generated or supplied externally. This feature is useful for compensating for factors which influence the applied magnetic field such as variations in specimen thickness.

The basic electronic components of the system are contained in modules which are inserted into a power supply case (Refer to Figure B1). The magnetizing section comprised of the waveform generator, power amplifier and magnetic feedback circuitry, is contained in the Detection Module along with the post-amplifier and detector-processor. The waveform generator provides the basic triangular waveform for cyclically magnetizing the specimen. This waveform is used as the input to a power amplifier, the output of which is a linearly varying current at sufficiently high voltage to drive the coil of the magnet. The frequency, rate of change and amplitude of the magnetizing current are all adjustable from the front panel of the instrument. A connector is provided at the rear of the instrument for supplying an external magnetizing waveform if desired. The Barkhausen Noise signal is available at a front panel connector labeled BARK. SIG. In addition, the amplitude-detected envelope of the Barkhausen Noise signal is available at a front panel connector labeled BARK. SIG. ENV.

4208

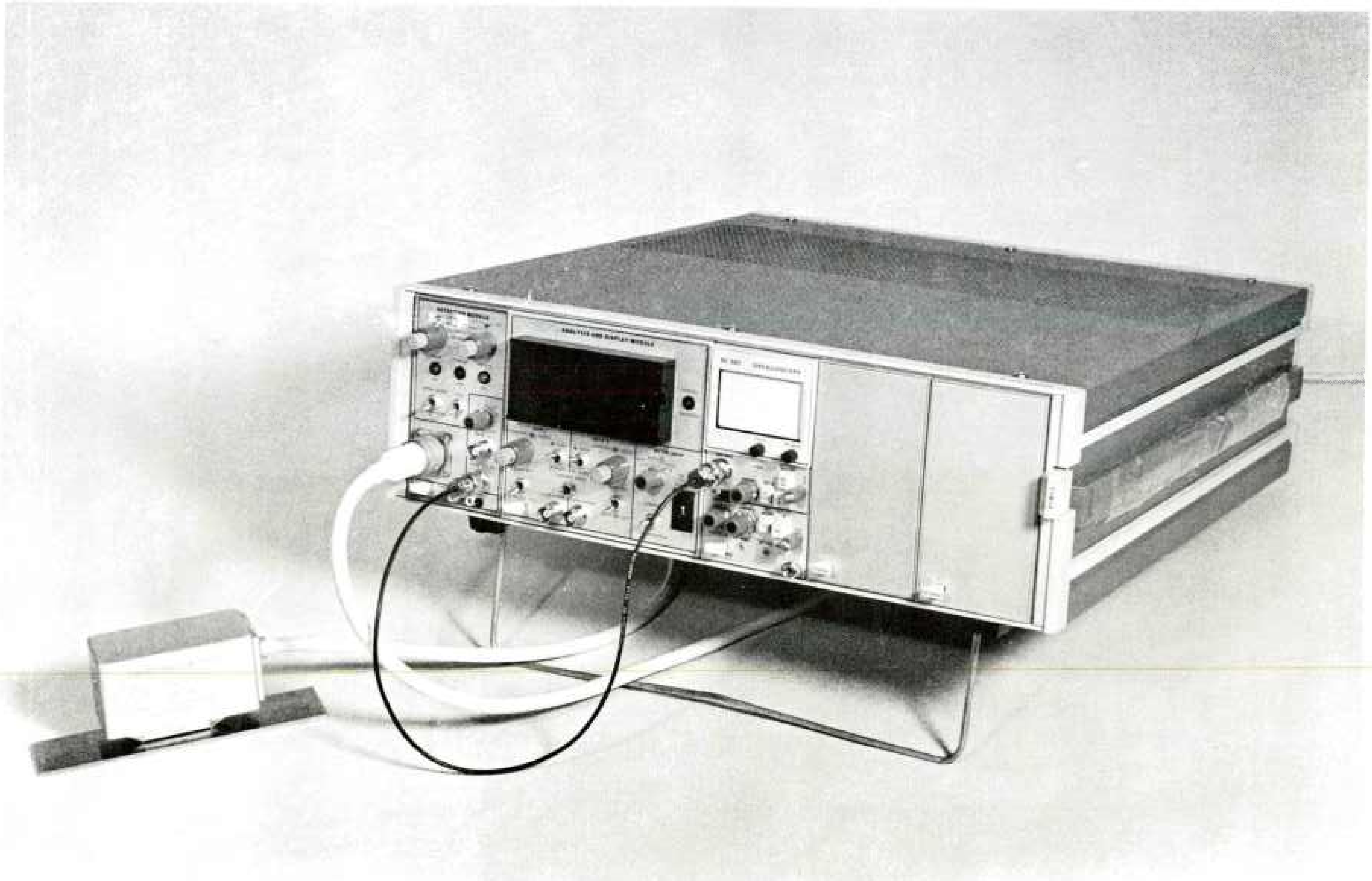

FIGURE B1. BARKHAUSEN NOISE STRESS MEASUREMENT SYSTEM

4149

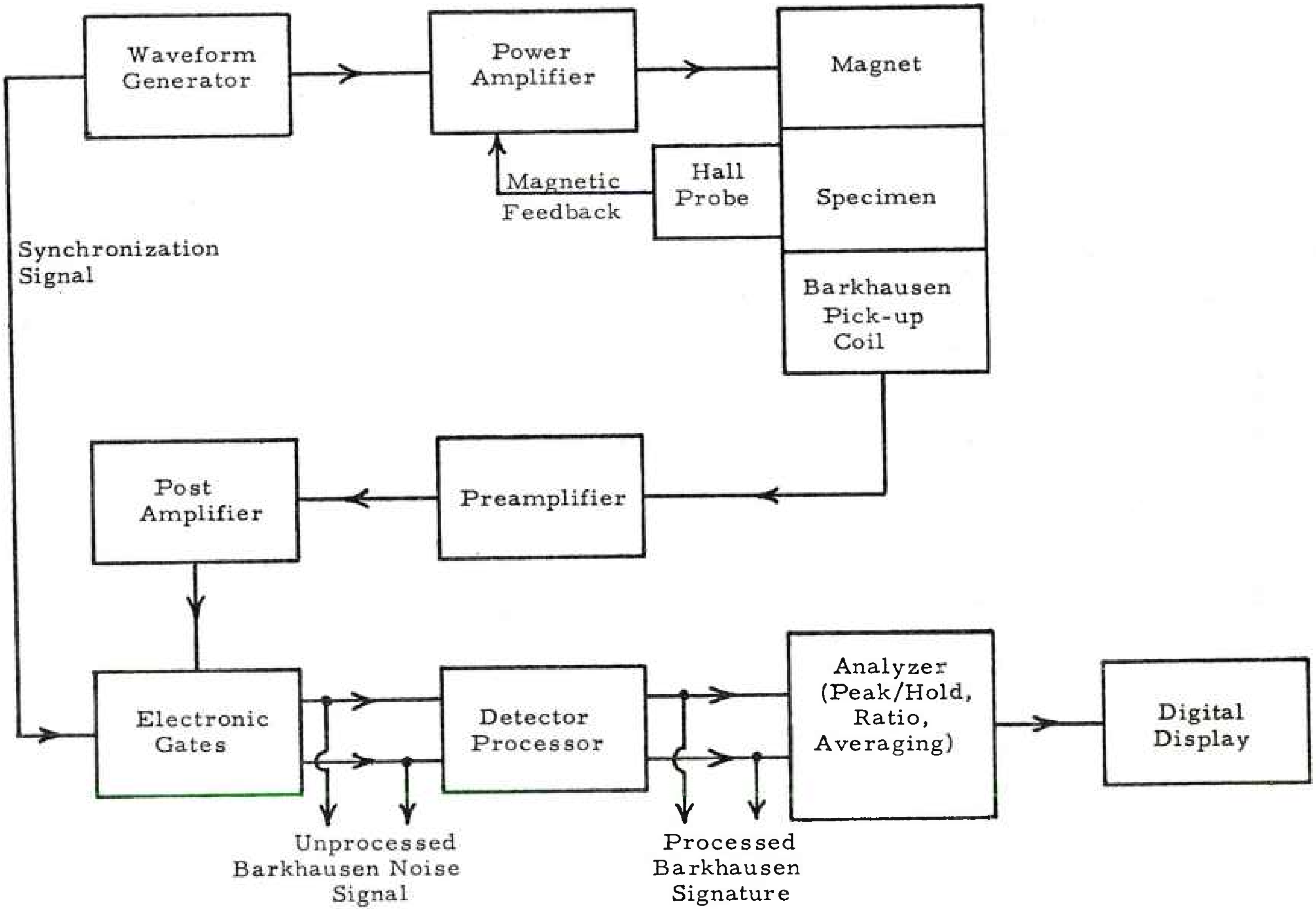

FIGURE B2. BLOCK DIAGRAM OF BARKHAUSEN NOISE INSTRUMENTATION SYSTEM

In the Analysis and Display Module are contained gating circuitry signal analysis circuitry and a digital display. The electronic gating system allows two portions of either the Barkhausen Signal or the Barkhausen Signal Envelope to be selected for further analysis. The gates are adjustable in width and position relative to a synchronizing signal derived from the waveform generator. The signal analyzer section consists of peak/hold circuitry to capture and retain the maximum voltage of the Barkhausen Signal Envelope resulting during the "on" time of each gate, and also ratio circuitry to provide a voltage proportional to the ratio between the maximum voltage values obtained from the two gates. The voltage from either gate or the ratio of these voltages is switch-selectable for digital display on a panel meter. In addition, averaging circuitry is provided so that the average of a selectable number of readings can be displayed as well as the individual instantaneous readings.

A modular oscilloscope is included in the instrumentation system for monitoring the Barkhausen Noise signals or other waveforms of interest. The two modules located at the far right of the instrument (See Figure B1) are storage modules to be used for storage of the hand-held Barkhausen detection probe and cables.

Additional performance and operational details can be found in the Operating Instruction Manual prepared for the Army Materials and Mechanics Research Center, Watertown, Massachusetts under Contract No. DAAG46-76-6-0028.

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ADVANCED SIGNAL ANALYSIS AND INSTRUMENTATION FOR BARKHAUSEN STRESS MEASUREMENT IN STEELS -
G. A. Matzkanin and G. L. Burkhardt
Southwest Research Institute
San Antonio, Texas 78284

Technical Report AMMRC CTR 77-22, September 1977
38 pp - illus - tables, Contract DAAG-46-76-C-0028
D/A Project 76M6350, AMCMS Code 53970M6350
Final Report, 15 Dec. 1975 to 28 Oct. 1977

AD ____________

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Key Words
Nondestructive Testing
Residual Stress
Barkhausen effect
Ferromagoetic materials
Magnetic detectors
Instrumentation
Magnetic Properties

Advanced methods of signal analysis were investigated as a means of improving instrumentation for Barkhausen noise stress measurement. Methods employed included pulse-sorting and pulse-counting, correlation and probability measurements, and spectrum analysis. Specimens of AISI 4340 steel and AISI 4130 steel were studied. It was found that the Barkhausen noise auto-correlation function, amplitude probability distribution, and amplitude probability density correspond closely to the comparable functions obtained from random noise. These statistical functions were found to be independent of magnetization rate and probe liftoff but slightly dependent on stress. Cursory experiments indicated that reducing the detector bandwidth may provide a means of increasing the stress sensitivity of these parameters. Detailed analysis of processed Barkhausen noise signals and results of pulse-counting experiments indicate that the Barkhausen signal ofteo is composed of two or more parts which respond differently to stress. Experiments oo specimeos stressed in uniaxial tension and cantilever bending showed that the shapes of the Barkhausen signals and the statistical characteristics depend upon the mode of loading. Based on the results of this program, an improved Barkhauseo stress measuriog instrument was developed, fabricated, and delivered to the Army Materials and Mechaoics Research Center.

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Southwest Research Institute
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Technical Report AMMRC CTR 77-22, September 1977
38 pp - illus - tables, Contract DAAG-46-76-C-0028
D/A Project 76M6350, AMCMS Code 53970M6350
Final Report, 15 Dec. 1975 to 28 Oct. 1977

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Key Words
Nondestructive Testing
Residual Stress
Barkhausen effect
Ferromagnetic materials
Magnetic detectors
Instrumentation
Magnetic Properties

Advanced methods of signal analysis were investigated as a means of improving instrumentation for Barkhausen noise stress measurement. Methods employed included pulse-sorting and pulse-counting, correlation and probability measurements, and spectrum analysis. Specimens of AISI 4340 steel and AISI 4130 steel were studied. It was found that the Barkhausen noise auto-correlation function, amplitude probability distribution, and amplitude probability density correspond closely to the comparable functions obtained from random noise. These statistical functions were found to be independent of magnetization rate and probe liftoff but slightly dependent on stress. Cursory experiments indicated that reducing the detector bandwidth may provide a means of increasing the stress sensitivity of these parameters. Detailed analysis of processed Barkhausen noise signals and results of pulse-counting experiments indicate that the Barkhausen signal ofteo is composed of two or more parts which respond differently to stress. Experiments on specimens stressed in uniaxial tension and cantilever bending showed that the shapes of the Barkhausen signals and the statistical characteristics depend upon the mode of loading. Based on the results of this program, an improved Barkhausen stress measuring instrument was developed, fabricated, and delivered to the Army Materials and Mechanics Research Center.

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
ADVANCED SIGNAL ANALYSIS AND INSTRUMENTATION FOR BARKHAUSEN STRESS MEASUREMENT IN STEELS -
G. A. Matzkanin and G. L. Burkhardt
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