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Acoustic Emission Testing Program: Progress Report on Tensile Testing Through October 1970

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Acoustic Emission Testing Program: Progress Report on Tensile Testing Through October 1970

by

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T. H. Feiertag

ACOUSTIC EMISSION TESTING PROGRAM:
PROGRESS REPORT ON TENSILE TESTING THROUGH OCTOBER 1970

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D. R. Schuyler II
T. H. Feiertag

ABSTRACT

Development of an acoustic emission testing program was initiated to broaden the nondestructive testing capability of the Laboratory. Acoustic emission is created in materials as they undergo stress relief mechanisms and may be detected by high gain electronic amplification equipment. A program of conducting tensile tests on various materials while monitoring with acoustic emission equipment was undertaken. This furnished background information which would be useful for predicting and evaluating acoustic emission behavior of structures more complicated than tensile samples.

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1. INTRODUCTION

The development of an acoustic emission testing program was initiated to broaden the capability of the nondestructive testing group of the Laboratory. Basically, acoustic emission has been defined as the stress waves given off by solid materials as the result of stress relaxation.[1,2] Mechanisms such as dislocation formation, pile-up, breakaway, crack formation and propagation, twinning, and grain boundary slip have all been suggested as sources of acoustic emission.[1,2,3,4] Events that may be monitored by emission from these mechanisms may therefore include microyielding, aging, recovery, fatigue, creep, and diffusionless phase changes.[4,5,6,7]

The acoustic emission from a material is detected by a piezoelectric transducer attached to the sample. The transducer is excited by the emission, resonates at its own frequencies but does not reproduce the frequency content of the emission.

Emission frequencies range from the audible up to the MHz range. The upper limit of frequencies is not known. The frequency spectrum from an emission source depends upon the speed at which events occur, their duration, resonances of the system, and attenuation due to intermediate materials located between the transducer and the sample (coupling materials such as grease, resin, or metal).[1] The high frequency components of the spectrum are most affected by attenuation and therefore will be damped out first. With this attenuated frequency spectrum, and with the further alteration of the signal by the transducer itself, low emphasis is placed on the monitoring of the signal according to frequency.

What is of concern then is the amplitude of the emission; some emissions occurring as a multitude of low-amplitude (energy) pulses and others as less frequent, high-amplitude pulses. The output of the amplifying system comprises both emission signals and background noise from the test and detection equipment. Hopefully, the detection electronics may then be developed to filter unwanted background noise and record only meaningful emission from the sample. The effort has therefore been placed on looking at the number of pulses with energies above arbitrary levels versus a second variable such as time, load, strain, or temperature. The emission may then be plotted as either a rate occurrence (counts/second) or a summation of counts.

Various programs within the Laboratory have shown acoustic emission arising during pressure vessel proof and failure tests, cracking of graphite-carbide composite materials from thermal stress tests, cracking and stress relief phenomenon from welding tests, martensitic phase changes from thermal cycling tests on Au-Cd alloys (beta-field compositions), and during tensile testing of several metals.

This report presents data on several materials (in various conditions of heat treatment) that were tensile tested while being monitored by acoustic emission equipment. Acoustic emission was usually displayed both in a count-rate mode and in a total-counts summation and presented with the load-elongation curve of the sample. The low amplitude emission comprised most of the signal generated and constitutes most of the count-rate curve. The high-amplitude "burst" emission was apparently not a great part of the emission of most samples and is best observed on the total-counts curve.

The intent of this report is to present the acoustic emission data for a wide variety of materials for background information. It is not the intent to analyze the acoustic emission behavior with respect to the properties of the materials or to make a correlation to possible physical events occurring in the materials.

II. MATERIALS AND EXPERIMENTAL PROCEDURES

A. Materials

Several metals have been tensile tested over the period December 1968 through October 1970, and are listed in Table 1.

TABLE I

LIST OF MATERIALS TESTED

Material	Manufacturer
Aluminum, Type 1100[8]	Unknown
Aluminum, Type 2024[9]	Kaiser Aluminum
Aluminum, Type 6061[10]	Kaiser Aluminum
Copper, ETP[11]	Unknown
Berylco-25[12]	Kawecki Berylco Industries
Iron[13]	Armco Steel Corporation
SAE 1019 Carbon Steel[14]	Unknown
304L Stainless Steel [15]	United States Steel
347 Stainless Steel[15]	Republic Steel Corporation
Almar-362[16]	Allegheny Ludlum Steel Corporation
HP-9-4-20[17]	Republic Steel Corporation
Vascomax-250[18]	Vanadium-Alloys Steel Company
Nickel-200[19]	International Nickel Company
Inconel-718[20]	International Nickel Company
Titanium (Ti-50A)[21]	Titanium Metals Corporation of America

Their nominal chemical compositions are listed in Appendix A (obtained from the references indicated in Table 1). Both the Armco iron and 1100 aluminum were analyzed at this Laboratory and included in the analyses listed in Appendix A. The metals, received in various mill shapes and heat-treat conditions, were machined to tensile test samples of the general shape shown in Fig. 1. Various reduced section lengths and cross sections were machined with the width of the reduced section kept below 0.4 in. since the pinholes were uniformly 0.5 in. in diam. The reduced section was located nearer one end to allow positioning of the transducer.

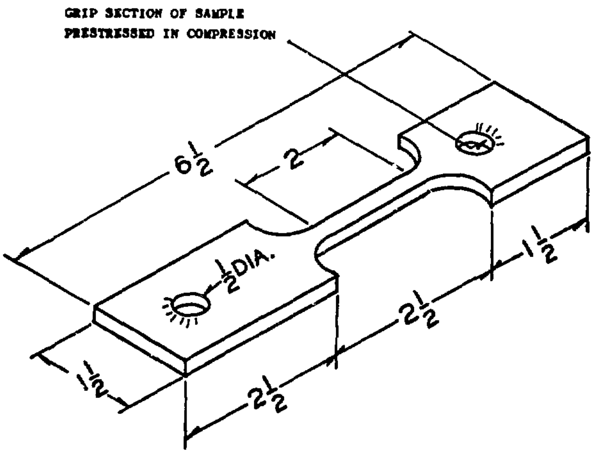

Fig. 1 - Typical Tensile Sample Showing Pin Grip Design According to ASTM Std E8-69. ASTM Std Dimensions Modified in Various Dimensions to Suit Material Strength and Test Situation.

After machining, the tensile samples were given various heat treatments in air, argon, or vacuum. The summary of heat treatments for all samples is given in Appendix B. After heat treating, the pin-holes on most of the samples were pre-stressed by inserting a 0.5-in. dowel pin and compressing the load-bearing portion of the samples (Fig. 1) with a load in excess of the expected test load.

B. Testing Procedures

Essentially three facets of the testing were involved - tensile testing, acoustic emission detection, and the merging of those two pieces of information for evaluation. The entire test setup is shown in Fig. 2 and illustrates the compact nature of the acoustic emission equipment (this was not the actual equipment used for the tests covered in this report). The following sections will be devoted to describing the tensile-test procedures, the acoustic emission electronic equipment setups, and the method used to assemble the two sets of data into a reasonable presentation. Some information concerning test equipment settings is listed in Appendix C.

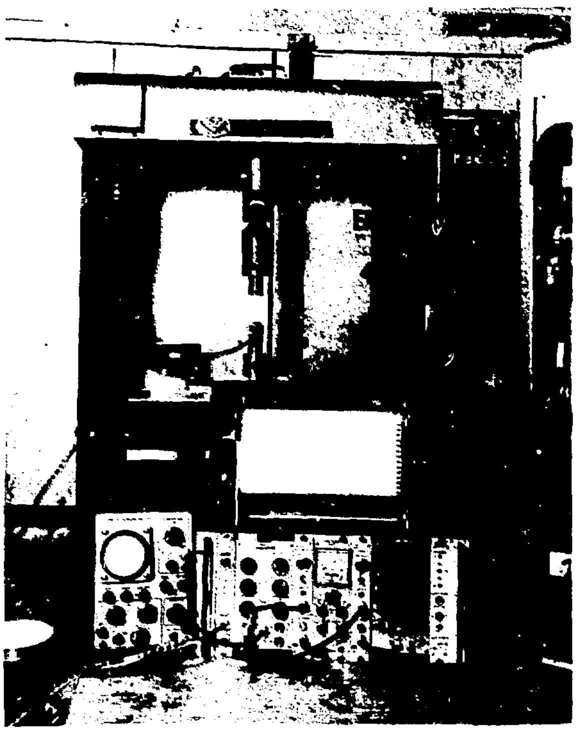

Fig. 2 - Test Setup Showing Tensile Test Machine and the Acoustic Emission Detection Equipment in Foreground.

1. Tensile Testing Procedures

An Instron Corporation floor model TT-C instrument (10,000 lb capacity) was used to perform tensile tests. Several crosshead speeds were used, 0.02, 0.05 and 0.5 in./min with the 0.05 in./min speed the most common. The constant-speed chart drive mode was used for all tests (2 in./min), therefore no extensometer was used for strain measurement. This produced tensile test curves of load vs total elongation. The elongation was distributed over the as-machined reduced section which varied from 1 to 2 in. (shoulder to shoulder) and 0.6 to 1.6 in. in the gage section. The elongation shown on the charts is 0.025 in./in. of chart for the 0.05 in./min crosshead speed. The strain would be based on this elongation and the gage length listed in Appendix C for each sample. As can be seen, the samples were strained at a constant rate of elongation, none of the tests being performed at a constant load rate.

The sample was placed in the Instron (Fig. 3) by using a dowel pin and attaching the transducer to the large section with a rubber band (grease was used as a coupling medium). No pre-load was given any sample other than that which developed during attachment to the Instron (this was found to range from 0 to 30 lb in either tension or compression).

2. Acoustic Emission Electronics

Several combinations of detection equipment were used during testing operations, but for the data presented in this report, only two setups were used. Instrument group number 1 is shown in Fig. 4 and was used for the tests performed on the Almar-362, HP-9-4-20, Vascomax-250 and

Inconel-718 alloys. Instrument group number 2 is illustrated in Fig. 5 and was used for all of the other alloy tests. As can be seen from these block diagrams (Figs. 4 and 5), the major difference in the setups was that different bandpass filters were used. However, the overall system performances were essentially the same since the gain for each was adjusted by advancing it until the ratemeter would just count the highest peaks of the electronic noise at the output of the post-amplifier.

For both systems the total gain from the preamp input to the linear ratemeter was about 95 db and to the digital ratemeter 85 db. The difference in gain was achieved by using different threshold settings on the threshold discriminators. The transducer used had a sharp resonance peak at 156 kHz and its response at this peak was approximately -80 db referenced to 1 V per microbar. Since the linear ratemeter threshold was 150 mV, which is -16.5 db referenced to 1 V, the pressure pulse at the transducer that would give a pulse to the ratemeter would be on the order of 1 microbar. Since the transducer is resonant at 156 kHz, there is a ringdown of about ten cycles for each pressure pulse into the transducer. Because a stronger pulse will give more ringdown pulses above the threshold than a weaker pulse, it is impossible to give any relation between either the count rate or the total counts and the number of events occurring in the test sample.

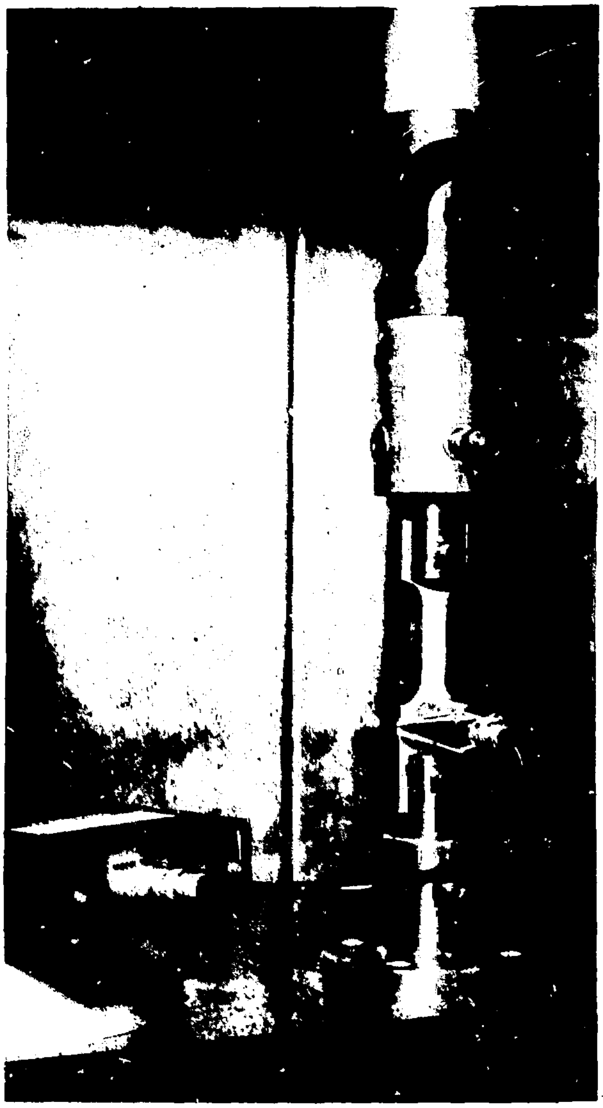

Fig. 3 - Tensile Sample as Loaded in the Test Machine and Showing the Attachment of the Transducer.

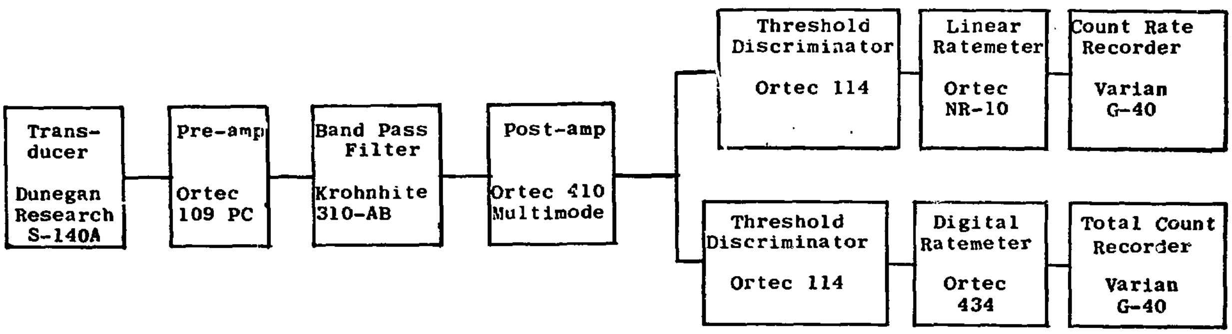

Fig. 4 - Acoustic Emission Equipment, Group Number One.

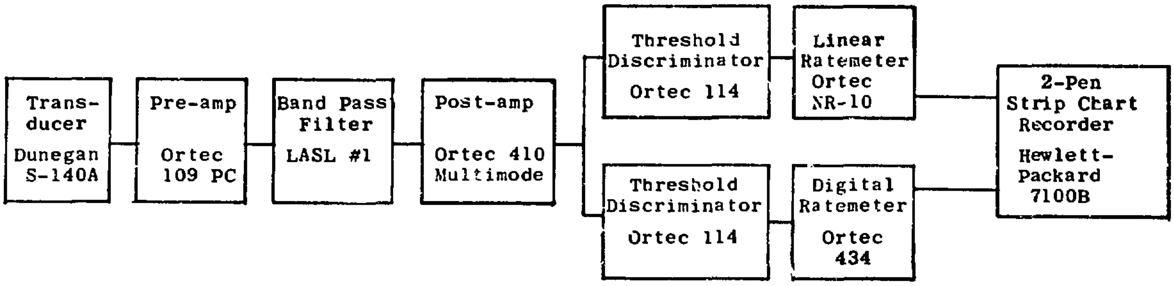

Fig. 5 - Acoustic Emission Equipment, Group Number Two.

The bandwidth of the group 1 electronics was $f_H - f_L = 200$ kHz - 83 kHz = 127 kHz. The LASL-designed filter used for the group 2 electronics gave a much sharper bandpass intended to eliminate ambient noise. The system bandpass with this filter was $f_H - f_L = 173$ kHz - 146 kHz = 27 kHz.

No consistent determination of background noise levels, either with or without the transducer mounted to the tensile sample, was made but from time to time it was observed in the vicinity of 150 mV RMS at the ORTEC 410 output.

3. Presentation of Data

Tracing of the tensile test and acoustic emission curves was performed at the same chart speeds to allow coordination of the data. The three separate charts, the load-elongation curve (really a load-time display), the acoustic emission count rate vs time, and the total counts vs time curves were placed adjacent to each other with identical origins. In the Appendix D illustrations, (see Fig. D1(a)) the load-elongation curve is on the bottom, the count-rate curve above it, and, where applicable, the total-count curve on the top.

III. RESULTS AND DISCUSSION

Discussion of the test results will be divided into two sections; 1) results observed as a function of test conditions, including sample preparation and equipment and, 2) those results that show the influence of heat treatment on specific materials.

A. Influence of Test Conditions

The size effect of the reduced section of a sample is shown in Fig. D1* where D1(b) and D1(d) have cross sectional areas (and volumes) about 2.5 times those of D1(a) and D1(c). Comparing Fig. D1(a) with D1(b) (both are as-received material) it appears that the count-rate curve shows only a moderate increase with size. On the other hand, the total-counts curve shows an increase (counts compared at 1.5% past yield) although not in direct proportion to the size difference. Comparing Fig. D1(c) with D1(d) (both are annealed at 1085°C and air cooled) the same seems to hold true, i.e., the count rate is not affected much but the total counts are (counts compared at 3.0% strain past yield).

Other investigators [22] have indicated the necessity for pre-stressing the grip ends of samples, the pin-grip type being very easy to pre-stress. Figure D2 illustrates the effect of not pre-stressing the sample ends (Fig. D2(b)) on the acoustic emission. It may be observed that a general increase in count-rate background results throughout the entire test, as well as a twofold increase in total counts.

The effect of a mis-positioned transducer is shown in Fig. D3. When the transducer was tightly attached to the sample, the emission appears as in Fig. D3(a). When it is poorly seated, allowing too

*Figures listed in this section are contained in Appendix D at the end of the report.

much coupling material (grease in this case) between the sample and transducer, a much reduced emission is observed as shown in Fig. D3(b).

The effect of an increase in strain rate by a factor of 10 may be seen in Fig. D4 which shows "overaged" 347 SS total counts affected a negligible amount and count rate affected only slightly. On the other hand, referring to Fig. D5, Type 1100 aluminum (solution annealed and water quenched) shows a gross effect on both the total counts and count rate. An increase of 10 in strain rate is matched very closely by the increase in total counts. It therefore appears that strain rate may or may not significantly influence the acoustic emission, based upon the material and its thermal and mechanical conditions.

Samples with gross defects, such as machined notches (Figs. D6 and D7), exhibit an expected decrease in count rate in the strain region past the yield point due to the reduced amount of material undergoing strain. As a result of notching, Inconel 718 (Fig. D6) and Vascomax 250 (Fig. D7) show count-rate peaks differing in amplitude and position in the region prior to and near the yield point.

The effect of cycling samples from zero load to a tensile load exceeding the previous load may be seen in Fig. D8 for several ironbase alloys and in Fig. D9 for several non-ferrous alloys. The well known irreversibility of the acoustic emission ("Kaiser Effect,"[1]) is well illustrated in both figures in that the previous load has to be equaled or exceeded for emission to resume. Several of these materials also exhibit the "unload emission" phenomenon (arrows, Figs. D1(d), D8, and D9) observed by others[5]. Since several of the materials exhibit this effect, it is felt that more-sensitive equipment conditions should be used on other materials in order to attempt to detect possible unload acoustic emission.

B. Effect of Heat Treatment on Specific Materials

1. Aluminum Alloys

Several aluminum alloys were tested in a variety of heat-treat conditions. Types 1100, 2024, and 6061 were tested in the as-received condition, the solution annealed and quenched state, and the aged condition. Figure D10 illustrates a comparison of the three alloys in the solution annealed and natural aged condition (Temper T4 without intermediate cold working).

Figure D11 shows Type 1100 aluminum in various states. Of particular interest is the effect of water quenching above a critical temperature (395°C) and the resulting increase in count rate (Fig. D11(b) vs D11(c)). Figure D12 shows the 2024 alloy behaving with high count-rate emission for all conditions evaluated. Figure D13 presents alloy 6061 and indicates a much lower count rate for all conditions than either of the two previous alloys.

2. Ferrous Alloys

Several ferrous alloys were tested in a variety of heat-treat conditions. These alloys consist of Armco iron, SAE 1019 carbon steel, Types 304L and 347 stainless steels, Almar 362, HP-9-4-20, and, Vascomax 250.

Armco iron is illustrated in Fig. D14 which shows only a moderate count rate and total counts until the water-quenched condition is obtained (Fig. D14(d)). The high increase is due to an increase in both high- and low-energy pulses.

A low carbon steel, SAE 1019, is illustrated in Fig. D15 and shows very high count rate & total count response in all the conditions of heat treatment. It is interesting to note that this material in the as-received condition (Fig. D15(a)) shows a very low emission, most likely resulting from the effects of the manufacturers' cold rolling. Increasing the tempering temperature from 288°C to 429°C to 594°C (Figs. D15(c), D15(d), and D15(e)) progressively increases the total counts from 32K to 55K to 72K. A maximum in the count-rate peak is promoted by the temper treatment at 429°C (Fig. D15(d)). The austenitizing temperature of 790°C shows a higher count rate in the quenched condition (Fig. D15(b) than it does in the air cooled condition (Fig. D15(f)). However, the total counts are just the reverse, the water quenched showing 80K and the air cooled about 160K. Generally, the peak in count rate occurred at slightly more strain than the 0.2% offset yield point. This material also shows a pre-emission at very low loads.

Type 304L stainless steel (Fig. D16) shows much emission activity before yield. The solution treated material (Fig. D16(b)) however, does show a count-rate peak slightly after yield as well as a large number of counts (Fig. D16(b)). If the solution treated material is then "aged" (Fig. D16(c)), the total counts are much less and the count rate after yield is also much less.

Type 347 (Fig. D17) stainless steel shows much the same behavior as the 304L. For emission activity before yield, the "overaged" material (Fig. D17(c)) shows very light emission. The solution treated and air cooled material (Fig. D17(b)) shows higher counts and count rate starting a little after yield. This material also exhibits the unload emission as can be seen in Fig. D17(b) (arrow).

The Almar 362 (Fig. D18) shows much activity before yield and a very definite peak in the count rate at yield in aged material (Figs. D18(c), (f) and (g)). Welded material shows a slightly higher activity level before yield in the aged material (Fig. D18(g)) and does not show the very definite count rate peak at the yield point that unwelded and aged material shows (Fig. D18(c)).

Alloy HP-9-4-20 (Fig. D19) shows much activity before yield and a very definite count-rate peak at or slightly before yield for the aged condition (Figs. D19(c) and (e)). The solution annealed condition (Fig. D19(b)) shows more activity in the count rate prior to yield but does not show much of a peak in the curve at the yield point.

Vascomax 250 (Fig. D20) also shows a great deal of activity before yield with the annealed material (Figs. D20(a), (b) and (e)) showing more than aged material (Figs. D20 (c), (d) and (f)). The aged condition promotes a large peak in the count-rate emission at the ultimate load while annealed material does not show much of a peak (Fig. D20(b)) and sometimes a dropping off of the count rate (Fig. D20(e)).

3. Other Alloys

Several other alloys were tested in a variety of heat-treat conditions and they include copper (ETP), a beryllium-copper alloy (Berylco-25), nickel, Inconel 718 and titanium (Ti-50A).

Copper (Fig. D21) generally did not show much emission for the strain rates used. Count-rate emission was most active before the yield point with most of it dropping off as soon as yield was reached. The count rate did seem to show a small increase with increasing heat treatment temperature.

The Berylco-25 (Fig. D22) also did not show much activity at any heat treatment but what there was occurred before the yield point. Strong activity was, however, observed just before failure (Figs. D22(c) and D22(d)).

Nickel (Fig. D23) was very interesting in that it showed repeated high count-rate peaks after yielding in material which was water quenched from heat-treatment temperatures of 427°, 534°, and 760°C (Figs. D23 (b), (c) and (d). The 534°C temperature (Fig. D23(c)) showed the higher rate pulses (20 to 22K vs 5 to 12K for the other two). This material did not appear to exhibit unload emission, at least for the sensitivity of the equipment used. The peak in count rate occurred slightly before yield, ranging from 40 to 80% of the yield load for the three heat-treat conditions.

Alloy Inconel 718 (Fig. D24) shows a count-rate peak at the yield point for both annealed (Fig. D24(a)) and aged (Fig. D24(b)) conditions. This alloy did show unload emission as well as some activity before yield.

Titanium (Fig. D25) did not show much activity in the as-received (Fig. D25(a)) and 539°C (Fig. D25(b)) heat-treat conditions. The heat treatments at 704°C (Fig. D25(c)) and 960°C (Fig. D25(d) and (e)) promoted extremely high count-rate activity, showing rates in excess of 100K counts/sec. The total count activity was low until the samples were heat treated at the 960°C temperature where they reached the 300 to 700K region, the air-cooled sample (Fig. D25(d)) having a higher count than the water quenched (Fig. D25(e)).

IV. CONCLUSIONS

Varying patterns of acoustic emission observed during the tensile testing of several metal alloys have indicated that preliminary testing of specimens is required to provide information for acoustic emission testing of actual engineering structures. Data contained in this report will, hopefully, serve as basic information which may be used to guide acoustic emission testing of such structures. It is also apparent that acoustic emission may be used as a basic research tool to provide valuable information about materials in stress situations.

Evaluations of the data indicate that the count-rate emission was very important when correlated to the load-elongation curve. Generally, all of the materials thus far tested exhibited peaks in acoustic emission count rate if the strain rate was sufficiently high. These peaks occurred at various positions with respect to the load-elongation curve obtained during the tensile test. Most of the heat-treat conditions showed peaks before macro-yield, many were at yield, and a few were subsequent to yield. Only two were located near the ultimate load position (Figs. D11 (b) and D15(f)). It was found that preliminary testing of materials and conditions to determine the characteristics of the count-rate peak would be necessary in order to predict properties of structures on the basis of yield strength.

The count-rate emission shows a basic pattern that includes a primary peak usually near yield, a decrease in rate after the primary peak to a near background rate somewhere near failure. The emission may tail off rather soon after the peak or it may continue at a reasonably high level, decreasing on a very gradual basis, especially if the material is quite ductile. Modifications of this basic curve may appear as: a) sharp singular pulses of emission (apparent within the limits of the response of the equipment) as shown in Figs. D23(b) and (c) near yield, b) bursts of emission which involved several stacked medium amplitude pulses (Figs. D11(b), D23 (b), (c), and (d)) after yield, c) secondary humps immediately following yield (Fig. D15) or as, d) secondary humps beyond the macro-yield (Figs. D11(b) and D15(f)).

These emission features are felt to arise from either : a) different sources (such as dislocation breakaway from either particles or other dislocations) or, b) the same source responding to different conditions of the material (such as dislocation breakaway from a small number of pinning sites vs a large number of pinning sites). Many acoustic emission sources are possible, as mentioned in the introduction, and these may each be contributing to the total emission for a sample but only one or two sources predominate for particular physical and mechanical states of the material. For these reasons, acoustic emission should serve as a valuable research tool to look at physical events within a sample during the test.

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APPENDIX A

NOMINAL CHEMICAL COMPOSITIONS

ALLOY	ELEMENT, WEIGHT PERCENT												
	Fe	Cr	Ni	C	Si	Mn	S	P	Nb + Ta	Mo	Ti	Co	Al
Armco Iron	99.75	1280 ppm metal impurities; 1180 non-metallic impurities											
Armco Iron*		0.003	0.001	0.028	0.002	0.03	0.01	0.004		<0.01	<0.001	0.003	<0.001
SAE 1019	Bal.			0.15 0.20		0.70 1.00	0.05 max.	0.04 max.					
304L Stainless	Bal.	18.0 20.0	8.0 12.0	0.03 max.	1.0 max.	2.0 max.	0.03 max.	0.045 max.					
347 Stainless	Bal.	17.0 19.0	9.0 13.0	0.08 max.	1.0 max.	2.0 max.	0.03 max.	0.045 max.	10X Carbon				
Vascomax 250**	Bal.		18.5	0.03 max.	0.1 max.	0.1 max.	0.01 max.	0.01 max.		3.25	0.2	8.5	0.1
Almar 362	Bal.	14.0 15.0	6.0 7.0	0.05 max.	0.3 max.	0.5 max.	0.03 max.	0.03 max.			0.7 0.9		
HP-9-4-20	Bal.	0.8	9.5	0.2	0.1 max.	0.35 max.				1.0		4.5	
Nickel*** (Inco 200)	0.40		Bal.	0.15	0.35	0.35	0.01						
Inconel 718****	11.0 23.0	17.0 21.0	50.0 55.0	0.08 max.	0.35 max.	0.35 max.	0.015 max.	0.015 max.	4.75 5.00	2.80 3.30	0.65 1.15	1.0 max.	0.2 0.8
Titanium (Ti-50A) *****	0.2 max.			0.1 max.							99.0		

* Armco iron analysed at this laboratory. Also shows 0.043 O_2, 0.004 N_2, 0.004 H_2 and 0.03 Cu (all in weight percent).

** Vascomax 250 also contains 0.003 Boron, 0.02 Zirconium and 0.05 Calcium.

*** Nickel 200 also contains up to 0.25 Copper.

**** Inconel 718 also may contain up to 0.006 Boron and 0.3 Copper.

***** Ti-50A also may contain a maximum of 0.25 Oxygen, 0.05 Nitrogen and 0.015 Hydrogen for ASTM B265, grade 2 Titanium.

APPENDIX A (cont'd)

NOMINAL CHEMICAL COMPOSITIONS

ALLOY	ELEMENT, WEIGHT PERCENT										
	Al	Cu	Mg	Mn	Si	Cr	Be	Co	Fe	Pb	OTHERS
1100 Aluminum	99.00	0.2 max.		0.05 max.							1.0 Fe + Si max. 0.10 Zn and 0.05 for others with a total maximum of 0.15
1100 Aluminum*		0.2	0.01	0.05	0.2	0.001	ND	ND	0.4	<0.01	0.012 O_2, <0.0005 C; 0.05 Zn
2024 Aluminum	Bal.	3.8-4.9	1.2-1.8	0.3-0.9	0.50 max.	0.10 max.			0.50 max.		0.25 maximum Zn and 0.05 max. for others with 0.15 total maximum
6061 Aluminum	Bal.	0.15-0.40	0.8-1.2	0.15 max.	0.4-0.8	0.15-0.35			0.7 max.		0.25 max. Zn, 0.15 max. Ti and 0.05 max. others with a total max. of 0.15
Copper, ETP		99.95								0.005 max.	Up to 0.102 Ag counted as Cu. 0.003 S max., 0.01 - 0.07 Oxygen, max.
Berylco-25		Bal.					1.8-2.0	0.2 min.		0.2-0.3	0.6 max. of Co + Ni + Fe

* Type 1100 Aluminum analysed at this laboratory

APPENDIX B

TENSILE SAMPLE CODE AND HEAT TREATMENTS

Material Sample Code	Condition and Heat Treatment
Aluminum, 1100	
Al-11-F-1	As-received (AR), F Condition
-2	484°C, 77 min., Water Quench (WQ) + Room Temperature (RT) Age, 16 mos.
-3	395°C, 3 min., WQ + RT Age, 16 mos.
-4	380°C, 90 min., WQ + RT Age, 16 mos.
Aluminum, 2024	
Al-24-3-1	AR, T3 Temper
-2	494°C, 77 min., WQ, may have gone to Eutectic Temperature, Refrigerated at 0°C, 16 mos.
-3	484°C, 77 min, WQ, + 193°C, 16.5 hrs., Air Cooled (AC)
-4	484°C, 77 min., WQ, + RT Age, 16 mos.
Aluminum, 6061	
Al-61-6-1	AR, T6 Temper
-2	530°C, 60 min., slow WQ, + Refrigerated at 0°C 16 mos.
-3	530°C, 60 min., slow WQ, + 160°C, 18 hrs., AC
-4	530°C, 60 min., slow WQ, + RT Age, 16 mos.
Copper, ETP	
Cu-1, -5, -9	AR (Hard Drawn)
Cu-10	148°C, 15 min., AC
Cu-2, -3, -11	175°C, 15 min., AC
Cu-4, -6, -12	221°C, 15 min., AC
Cu-7, -8	288°C, 15 min., AC
Berylco-25	
Cu-Be-1	AR (Half Hard)
-2, -3	806°C, 20 min., + 790°C, 40 min. WQ
-4, -5	806°C, 20 min., + 790°C, 40 min., WQ, + 377°C, 60 min. AC
-6	377°C, 60 min., AC
Armco Iron	
Fe-A-1, -2	AR
-3, -4	704°C, 30 min., AC
-5	704°C, 30 min., WQ
-6	495°C, 37 min., AC
SAE 1019 Steel	
Fe-19-1	AR (Mild Cold Rolled (CR))
-2	790°C, 30 min., WQ
-3	790°C, 30 min., WQ + 205°C, 15 min., AC
-4	790°C, 30 min., WQ + 425°C, 60 min., AC
-5	790°C, 30 min., WQ + 504°C, 60 min., AC
-6	790°C, 30 min., AC
304L Stainless	
S-304L-1	AR (Hot Rolled, Annealed and Pickled)
-2	1085°C, 30 min., AC
-3	1085°C, 30 min., AC + 815°C, 115 hrs., AC
-4	1085°C, 30 min., AC + 815°C, 115 hrs., AC, + 729°C, 2190 hrs., AC
347 Stainless	
S-347-1	AR (Hot Rolled, Annealed and Pickled)
-2	1085°C, 30 min., AC
-3	1084°C, 30 min., AC + 815°C, 115 hrs., Delayed WQ + 730°C, 347 hrs., AC
-4	1085°C, 30 min., AC + 815°C, 115 hrs., AC + 729°C, 2190 hrs., AC
-5	AR, Hot Rolled, Annealed and Pickled
-6	1085°C, 30 min., AC
-7	1084°C, 30 min., AC + 815°C, 115 hrs., Delayed WQ + 730°C, 347 hrs., AC
-8	1084°C, 30 min., AC + 815°C, 115 hrs., Delayed WQ
Almar 362	
AA-1	AR (Cold Worked and Annealed at 843°C), 835°C, 60 min., WQ
-2	835°C, 60 min., WQ + 488°C, 8 hrs., AC
-3	AR
AM-1	AR (815°C, 60 min., AC + 485°C, 8 hrs., AC) + 835°C, 60 min., WQ
-2	835°C, 60 min., WQ + 485°C, 8 hrs., AC
-3	AR
WQ-1	AR, (Electron Beam Welded)
-2	472°C, 3 hrs., WQ
-3	AR
-4	885°C, 10 min., WQ + 472°C, 3 hrs., WQ
-5	885°C, 10 min., WQ
-6	AR
HP-9-4-20	
HA-1	AR (Hot Rolled) + 475°C, 60 min., WQ
-2	835°C, 60 min., WQ
-3	AR
WE-1	AR, (840°C, WQ + Double Temper, 540°C, 2 hrs) and Welded
-2	AR, Welded
-3	AR, Welded
-4	AR, Welded
-5	AR, Welded and 472°C, 60 min., WQ

Material Sample Code	Condition and Heat Treatment
Vascomax 250	
VA-1	AR (Annealed)
-2	AR
-3	814°C, 1 hr., WQ
-4	AR
-5	AR (C R + 816°C Anneal) + 835°C, 60 min., WQ
-6	835°C, 60 min., WQ + 511°C, 3 hrs., AC
-7	AR
VH-1	AR (Aged)
-2	AR
-5	AR (816°C, 60 min., WQ + 510°C, 3 hrs., AC) + 835°C, 60 min., WQ
-6	835°C, 60 min., WQ + 511°C, 3 hrs., AC
-7	AR
WVA-1	AR (Aged and Then Welded)
-2	AR
-3	AR
-4	AR
-5	AR
-6	AR
VHT-1	AR (Aged)
-2	AR
V-250-A1	Annealed Soft
-A2	Annealed Soft, Notched
-A4	Annealed Soft
V-250-H2	Aged
-H5	Aged, Notched
Nickel 200	
Ni-2-1	AR (CR, Pickled and Annealed)
-2	427°C, 30 min., WQ
-3	534°C, 30 min., WQ
-4	760°C, 30 min., WQ
Inconel 718	
I-18-3	980°C, 30 min., WQ, Notched
-5	980°C, 30 min., WQ
-6	980°C, 30 min., WQ + 721°C, 19 hrs., AC
-7	980°C, 30 min., WQ. Ends not pre-stressed.
Titanium ASTM Grade 2	
Ti-50-1	AR (Probably 704°C, 2 hrs., AC)
-2 & -3	539°C, 30 min., AC
-4, -7, -8	704°C, 30 min., AC
-5	959°C, 32 min., AC
-6	959°C, 32 min., AC + 960°C, 30 min., WQ

APPENDIX C

TESTING INFORMATION

MATERIAL	REDUCED SECTION	GAGE SECTION		TENSILE TEST		ACOUSTIC EMISSION EQUIPMENT SETTINGS			
						Total Counts		Count Rate	
Sample Number	Length (in)	Area (in^2)	Vol. (in^3)	Load Range (lbs)	Elong. (%)	Thres-hold (mV)	Half scale (counts)	Thres-hold (mV)	Count Rate (c/s)
ALUMINUM, 1100									
Al-11-F-1	1.60	0.0986	0.1579	5K	31	550	10K	150	100K
Al-11-F-2	"	0.0982	0.1570	"	36	"	"	"	"
Al-11-F-3	"	0.0995	0.1592	2K	29	"	"	"	"
Al-11-F-4	"	0.0985	0.1577	5K	36	"	"	"	"
ALUMINUM, 2024									
Al-24-3-1	1.60	0.1024	0.1640	10K	16	550	10K	150	100K
-2	"	0.1023	0.1639	"	16	"	"	"	"
-3	"	0.1027	0.1641	"	9	"	"	"	"
-4	"	0.1024	0.1640	"	15	"	"	"	"
ALUMINUM, 6061									
Al-61-6-1	1.60	0.1020	0.1632	5K	13	550	10K	150	100K
-2	"	0.1014	0.1622	10K	20	"	"	"	"
-3	"	0.1021	0.1634	"	12	"	"	"	"
-4	"	0.1022	0.1636	"	18	"	"	"	"
ETP COPPER									
Cu-1	1.65	0.0377	0.0621	5K	27	550	10K	150	100K
-2	1.60	0.0373	0.0596	"	25	"	"	"	"
-3	"	0.0385	0.0614	2K	26	"	"	"	"
-4	"	0.0370	0.0591	5K	26	"	"	"	"
-5	"	0.0495	0.0791	"	27	"	"	"	"
-6	"	0.0491	0.0784	"	(1)	"	"	"	"
-7	"	0.0496	0.0791	"	29	"	"	"	"
-8	"	0.0494	0.0789	"	27	"	"	"	"
-9	"	0.0993	0.1588	"	30	"	"	"	"
-10	"	0.0987	0.1580	"	32	"	"	"	"
-11	"	0.0986	0.1579	"	(1)	"	"	"	"
-12	"	0.0984	0.1574	"	32	"	"	"	"
BERYLCO-25									
Cu-Be-1	1.60	0.0399	0.0638	10K	15	550	10K	130	100K
-2	1.65	0.0400	0.0660	"	56	"	"	"	"
-3	1.60	0.0398	0.0636	"	56	"	"	"	"
-4	"	0.0402	0.0643	Not tested, broke during pre-stressing.					
-5	"	0.0392	0.0627	10K	1.0	550	10K	130	100K
-6	"	0.0391	0.0625	"	3.5	"	"	"	"

(1) Sample not tested to failure

APPENDIX C

TESTING INFORMATION

MATERIAL	REDUCED SECTION	GAGE SECTION		TENSILE TEST		ACOUSTIC EMISSION EQUIPMENT SETTINGS			
						Total Counts		Count Rate	
Sample Number	Length (in)	Area (in^2)	Vol. (in^3)	Load Range (lbs)	Elong. (%)	Thres-hold (mV)	Half scale (counts)	Thres-hold (mV)	Count Rate (c/s)
ARMCO IRON									
Fe-A-1	1.60	0.0754	0.1206	10K	15	550	10K	150	100K
-2	"	0.0747	0.1196	"	14	"	"	"	"
-3	"	0.0755	0.1208	"	30	"	"	"	"
-4	"	0.0750	0.1200	2K	30	"	"	"	"
-5	"	0.0757	0.1210	5K	21	"	"	"	"
-6	"	0.0755	0.1208	"	23	"	"	"	"
STEEL, 1019									
Fe-19-1	1.60	0.0732	0.1171	10K	7	550	10K	150	100K
-2	1.55	0.0733	0.1135	"	7	"	"	"	"
-3	1.60	0.0734	0.1173	"	17	"	"	"	"
-4	"	0.0736	0.1178	"	15	"	"	"	"
-5	"	0.0735	0.1176	"	24	"	"	"	"
-6	"	0.0730	0.1168	"	29	"	"	"	"
304L STAINLESS									
S-304L-1	1.65	0.0839	0.1383	10K	59	550	10K	150	100K
-2	1.60	0.0832	0.1332	"	69	"	"	"	"
-3	"	0.0828	0.1325	"	71	"	"	"	"
-4	"	0.0818	0.1308	"	66	"	"	"	"
347 STAINLESS									
S-347-1	1.60	0.0324	0.0518	10K	51	550	10K	150	100K
-2	"	0.0330	0.0527	5K	52	"	"	"	"
-3	1.65	0.0328	0.0524	"	51	"	"	"	"
-4	1.60	0.0329	0.0525	"	42	"	"	"	"
-5	"	0.0812	0.1300	10K	57	"	"	"	"
-6	"	0.0814	0.1302	"	60	"	"	"	"
-7	"	0.0803	0.1284	"	43	"	"	"	"
-8	"	0.0794	0.1269	"	54	"	"	"	"
ALMAR 362									
AA-1	1.5	0.0320	0.0480	10K	7	500	10K	150	50K
-2	"	0.0351	0.0527	"	18	"	"	"	"
-3	"	0.0319	0.0478	"	6	"	"	"	"
AH-1	"	0.0319	0.0478	"	7	"	"	"	"
-2	"	0.0349	0.0523	"	18	"	"	"	"
-3	"	0.0292	0.0438	"	8	"	"	"	"
WA-1	0.6	0.0416	0.0249	"	10	"	100K	"	"
-2	"	0.0450	0.0270	"	11	400	"	"	"
-3	"	0.0452	0.0271	"	9	500	10K	"	"
-4	"	0.0446	0.0268	"	12	"	"	"	"
-5	"	0.0442	0.0265	"	10	"	100K	"	"
-6	"	0.0443	0.0266	"	11	-	-	100	"

APPENDIX C

TESTING INFORMATION

MATERIAL	REDUCED SECTION	GAGE SECTION		TENSILE TEST		ACOUSTIC EMISSION EQUIPMENT SETTINGS			
						Total Counts		Count Rate	
Sample Number	Length (in)	Area (in^2)	Vol. (in^3)	Load Range (lbs)	Elong. (%)	Threshold (mV)	Half scale (counts)	Threshold (mV)	Count Rate (c/s)
HP-9-4-20									
HA-1	1.5	0.0401	0.0600	10K	13	500	100K	150	50K
-2	"	0.0429	0.0642	"	11	"	"	"	"
-3	"	0.0400	0.0600	"	6	"	10K	"	"
WH-1	0.5	0.0436	0.0218	"	9	500	"	"	"
-2	"	0.0413	0.0206	"	9	250	"	"	"
-3	"	0.0419	0.0209	"	9	500	"	"	"
-4	"	0.0419	0.0209	"	10	"	"	"	
-5	"	0.0421	0.0210	"	9	"	"	"	"
-6	"	0.0419	0.0209	"	7	"	"	"	"
VASCOMAX 250									
VA-1	1.1	0.0480	0.0527	10K	15	-	-	100	50K
-2	"	0.0476	0.0524	"	16	-	-	"	"
-3	"	0.0480	0.0527	"	15	250	10K	150	"
-4	"	0.0322	0.0354	"	12	1000	999K	"	"
-5	1.5	0.0344	0.0516	"	14	500	100K	"	"
-6	"	0.0307	0.0460	"	7	"	"	"	"
-7	"	0.0317	0.0475	"	10	"	10K	"	"
VH-1	1.1	0.0319	0.0351	"	10	-	-	100	"
-2	"	0.0326	0.0356	"	10	250	100K	150	"
-5	1.5	0.0324	0.0486	"	7	500	"	"	"
-6	"	0.0344	0.0516	"	9	"	10K	"	"
-7	"	0.0327	0.0490	"	5	"	100K	"	"
VASCOMAX 250									
WVA-1	0.65	0.0419	0.0275	10K	2	-	-	100	50K
-2	"	0.0424	0.0278	"	4	-	-	"	"
-3	"	0.0433	0.0284	"	7	-	-	"	"
-4	"	0.0444	0.0291	"	9	-	-	"	"
-5	"	0.0424	0.0278	"	5	-	-	"	"
-6	"	0.0424	0.0278	"	6	-	-	"	"
VHT-1	1.1	0.0319	0.0350	"	10	-	-	75	100K
-2	"	0.0315	0.0346	"	11	-	-	100	"
V-250-A1	1.1	0.0412	0.0448	10K	-	-	-	-	50K
-A2	"	----	----	"	-	-	-	-	"
-A4	"	0.0484	0.0526	"	10	-	-	-	100K
V-250-H2	1.1	0.0327	0.0358	10K	-	-	-	-	100K
-H5	"	0.0320	0.0351	"	3.5	-	-	-	"
NICKEL-200									
Ni-2-1	1.60	0.0753	0.1203	5K	35	550	10K	150	100K
-2	"	0.0752	0.1202	10K	40	"	"	"	"
-3	"	0.0743	0.1188	5K	37	"	"	"	"
-4	"	0.0749	0.1197	10K	40	"	"	"	"

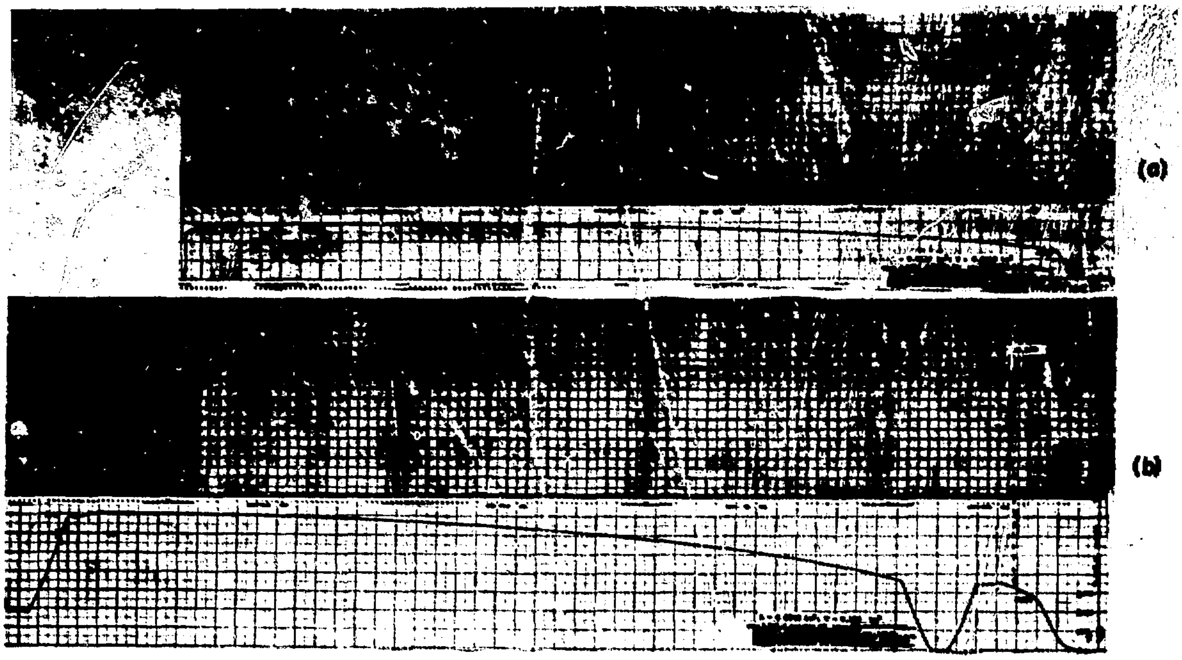
APPENDIX C

TESTING INFORMATION

MATERIAL	REDUCED SECTION	GAGE SECTION		TENSILE TEST		ACOUSTIC EMISSION EQUIPMENT SETTINGS			
						Total Counts		Count Rate	
Sample Number	Length (in)	Area (in^2)	Vol. (in^3)	Range (lbs)	Elong. (%)	Thres-hold (mV)	Half scale (counts)	Thres-hold (mV)	Count Rate (c/s)
INCONEL-718									
I-18-3	--	0.0530	----	10K	14	-	-	-	100K
-5	1.4	0.0599	0.0837	"	37	550	10K	150	"
-6	2.3	0.0421	0.0966	"	(1)	"	"	"	"
-7	--	----	----	"	--	-	-	-	"
TITANIUM									
Ti-50-1	1.1	0.0438	0.0482	5K		550	10K	150	100K
-2	"	0.0443	0.0487	10K		"	"	"	"
-3	"	0.0445	0.0489	5K		"	"	"	"
-4	"	0.0443	0.0487	10K		"	"	"	"
-5	0.6	0.0443	0.0266	5K		"	"	"	"
-6	"	0.0440	0.0264	"		"	"	"	"
-7	1.1	0.0221	0.0243	10K		"	"	"	"
-8	"	0.0221	0.0243	5K		"	"	"	"

APPENDIX D

(See Section III-A)



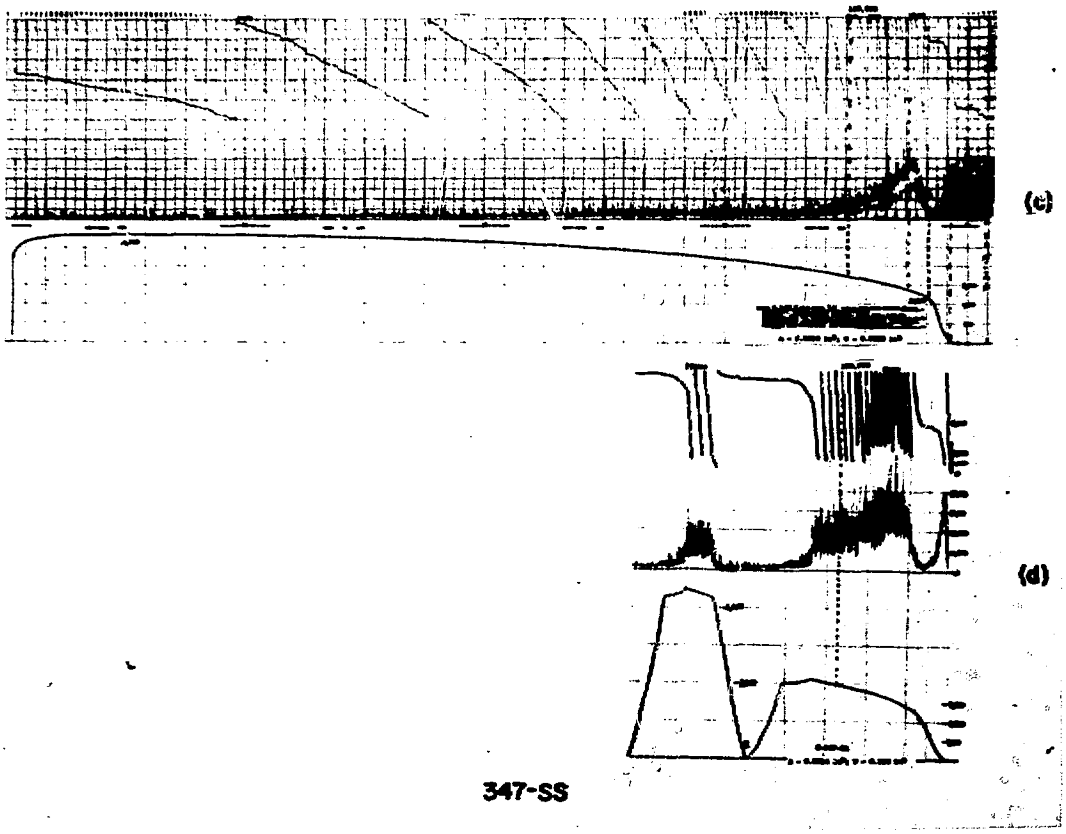


Fig. D1 - Effect of Sample Size on Acoustic Emission from As-Received (a and b) and from Solution Annealed and Air Cooled 347 Stainless Steel Material (c and d). The Samples Shown in (b and d) are About 2.5 Times the Cross Sectional Area and Volume Shown in (a and c). Note the Unload Emission at the Arrow on (d).

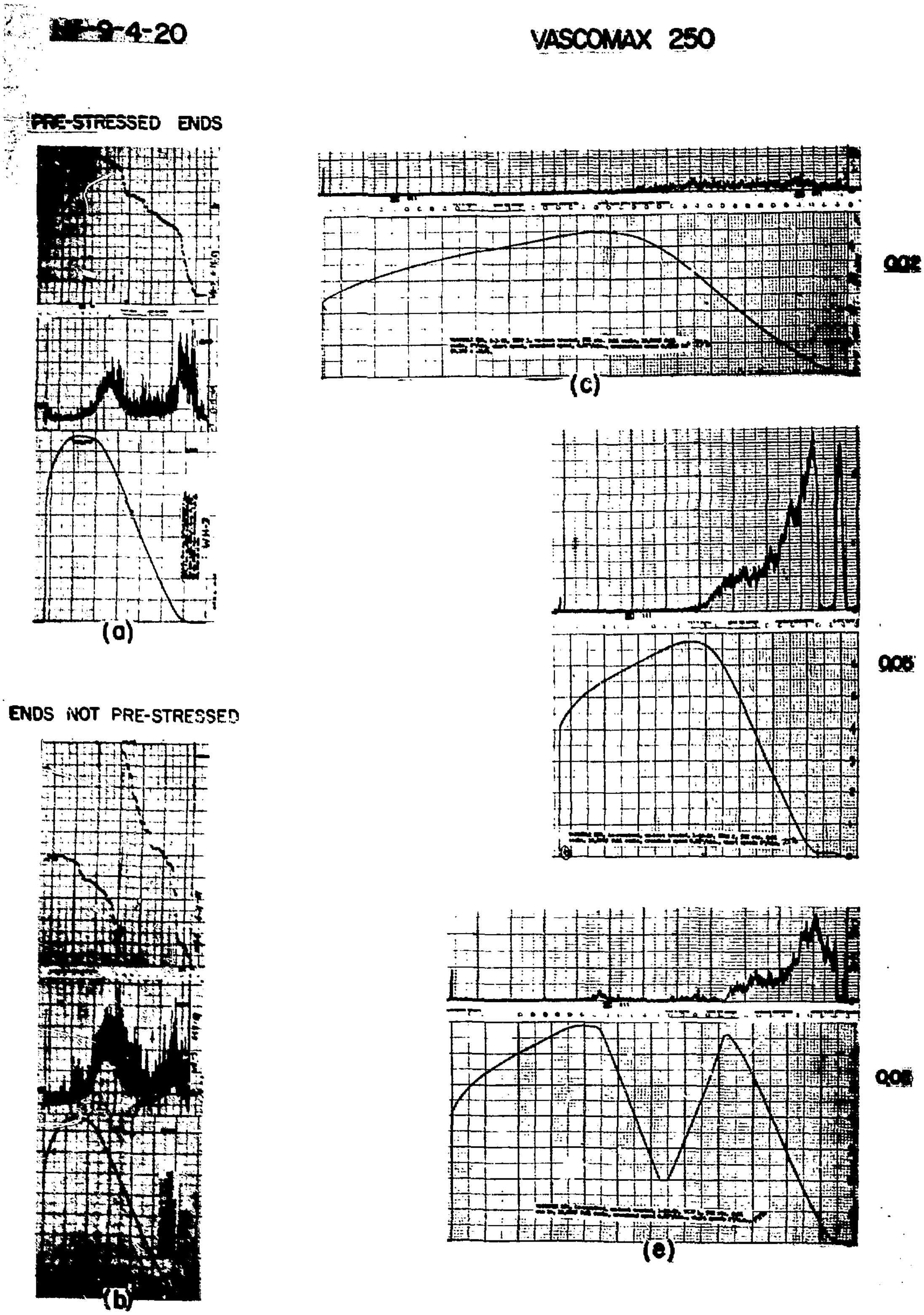


Fig. D2 - Effect of Not Pre-Stressing the Sample Pinholes. (HP-9-4-20 Alloy). The Sample with Pre-Stressed Holes is Shown in (a) and the Sample without in (b).

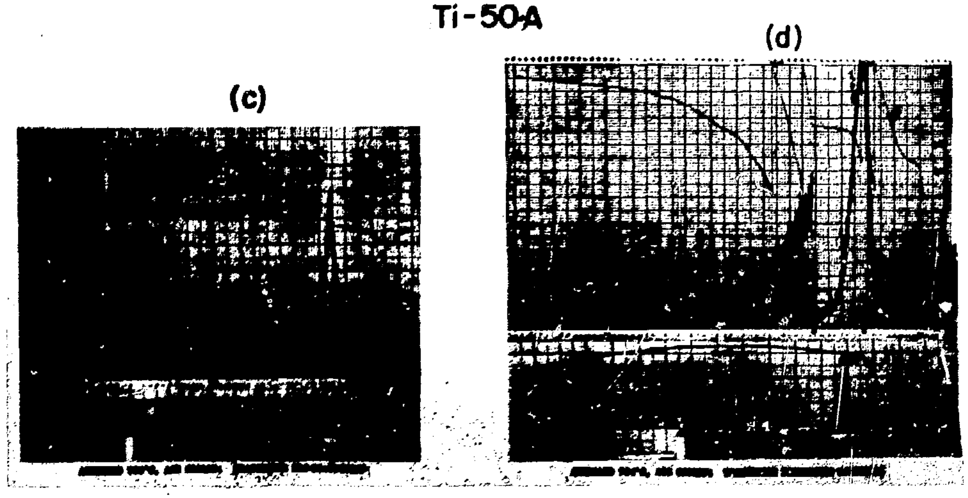


Fig. D3 - Effect of a Mis-Positioned Transducer (Titanium). Sample with Transducer Seated Tightly is Shown in (a) and the Sample with Poor Placement is Shown in (b).

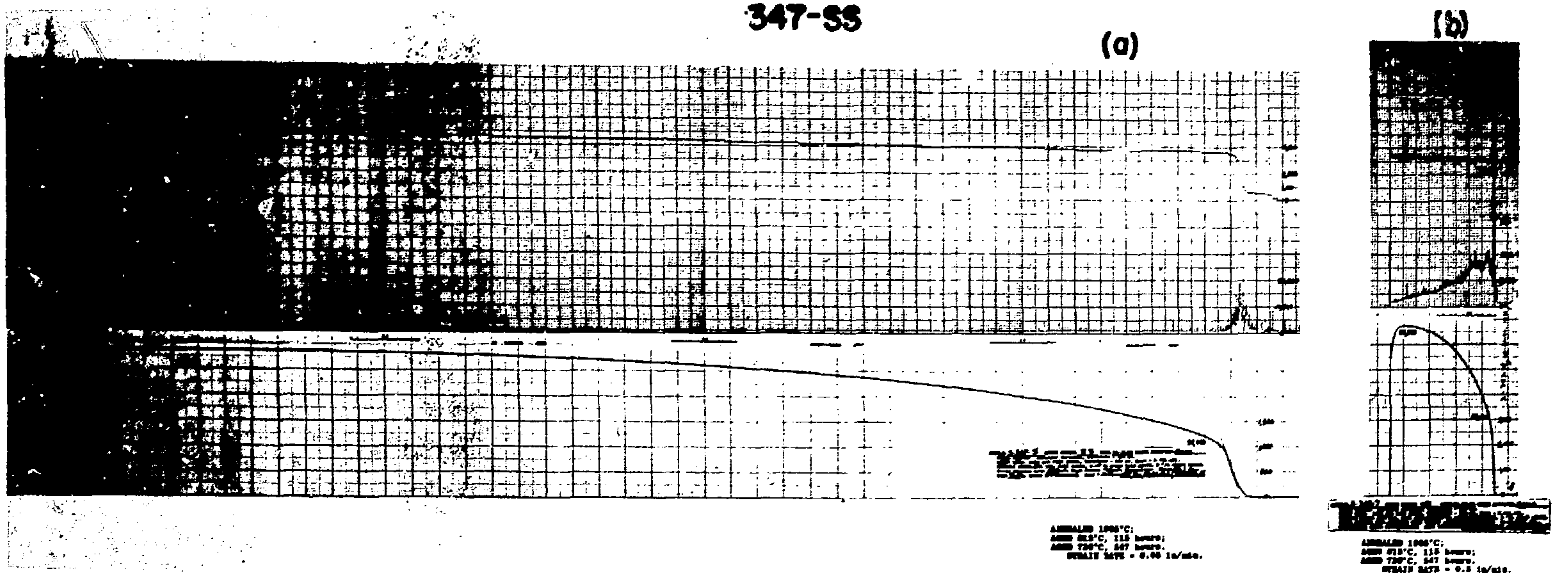


Fig. D4 - Effect of Strain Rate. Overaged 347 Stainless Steel Strained at 10 Times the Rate (b) of the Other Sample (a).

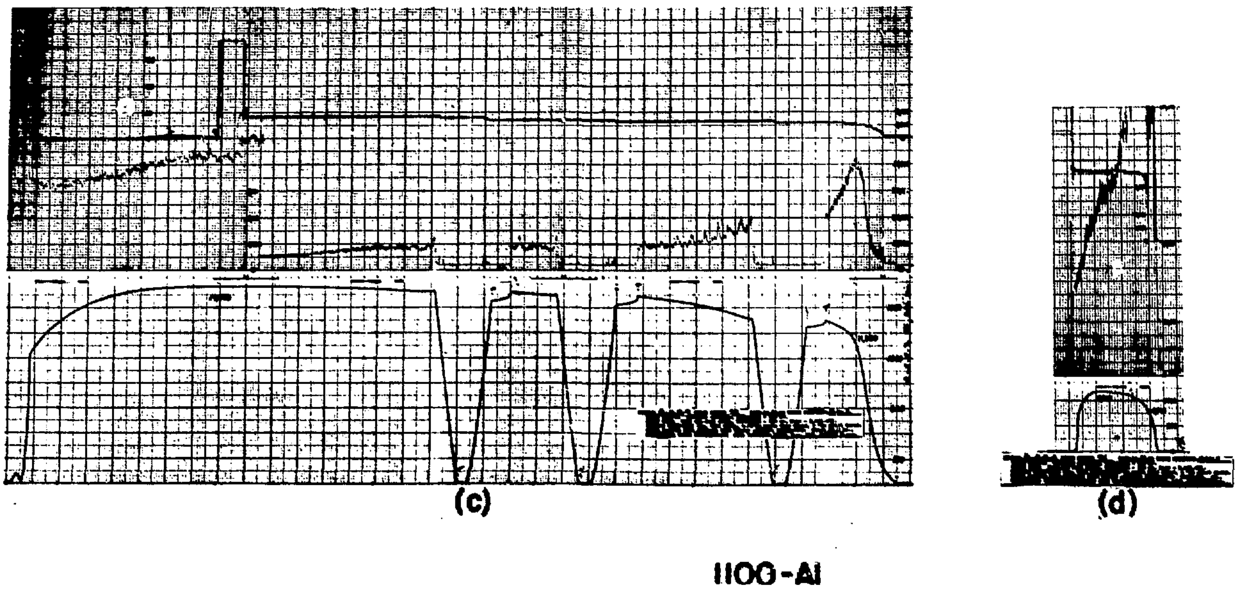


Fig. D5 - Effect of Strain Rate. Type 1100 Aluminum Strained at 10 Times (b) the Rate of the Other Sample (a).

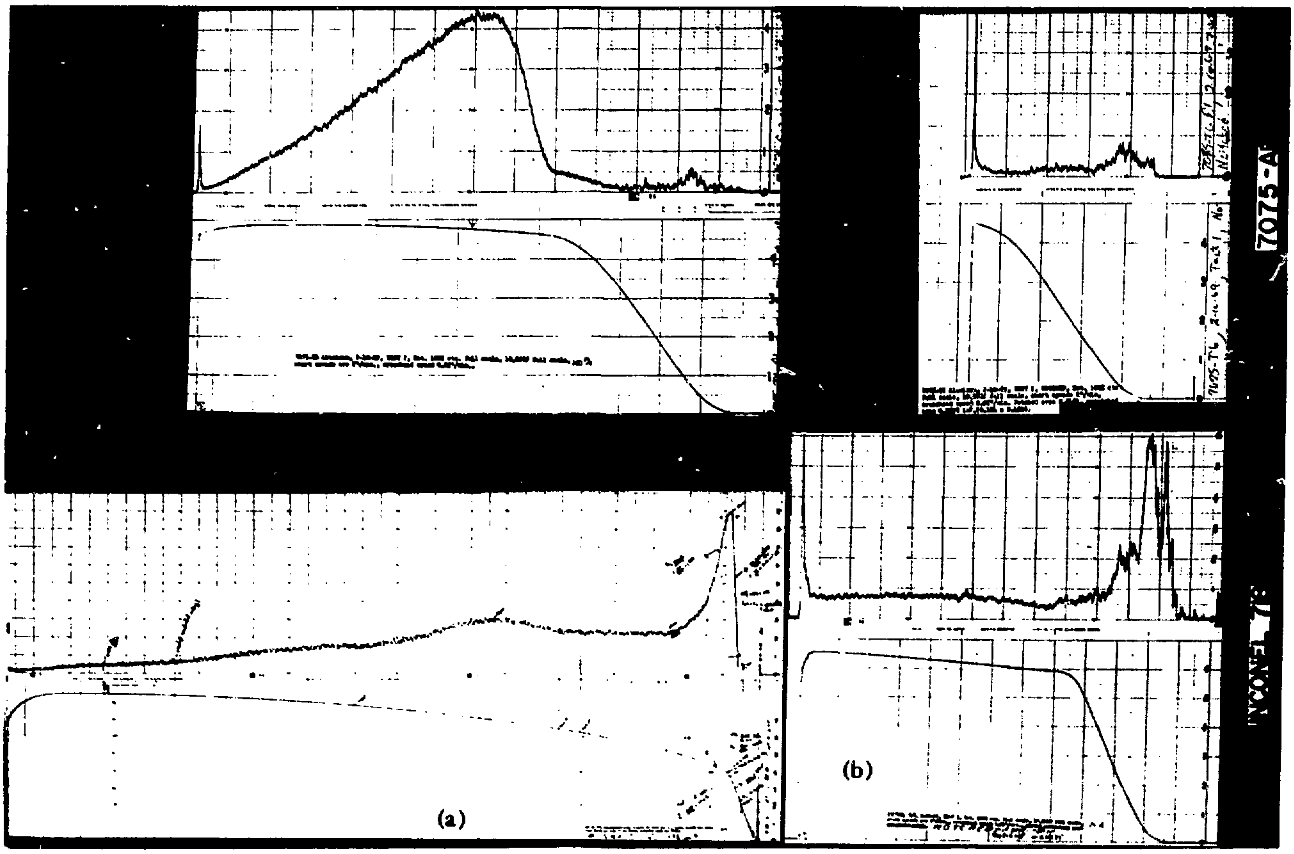


Fig. D6 - Effect of a Gross Defect (Machined Notch). Inconel-718 in the Solution Annealed and Quenched Condition in the Un-Notched (a) and Notched (b) Conditions.

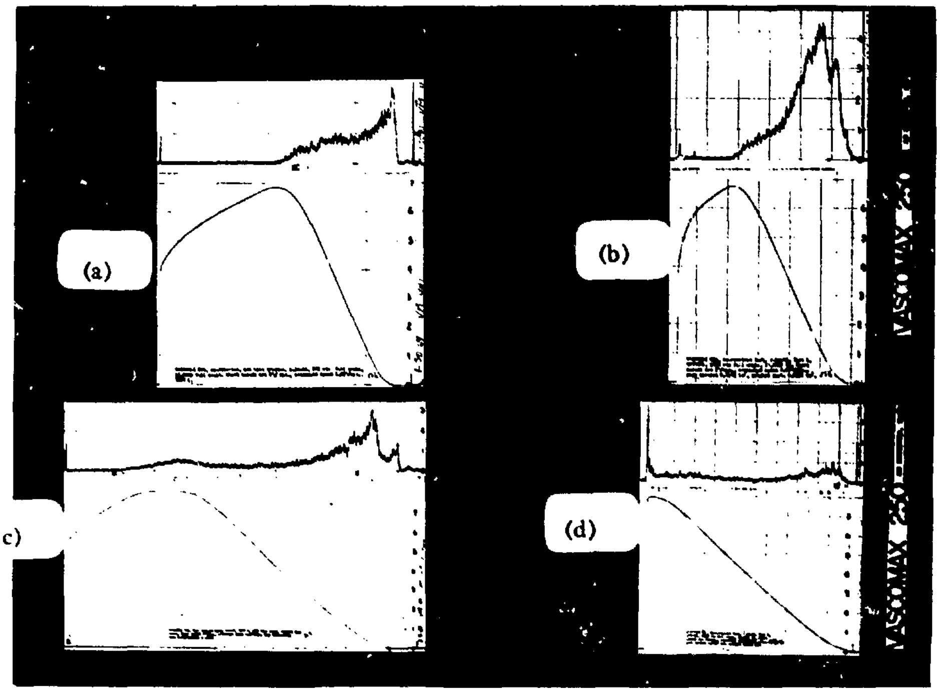


Fig. D7 - Effect of a Gross Defect (Machined Notch). Vascomax-250 in the Annealed Condition (a and b) and in the Aged Condition (c and d) without a Notch (a and c) and with a Notch (b and d).

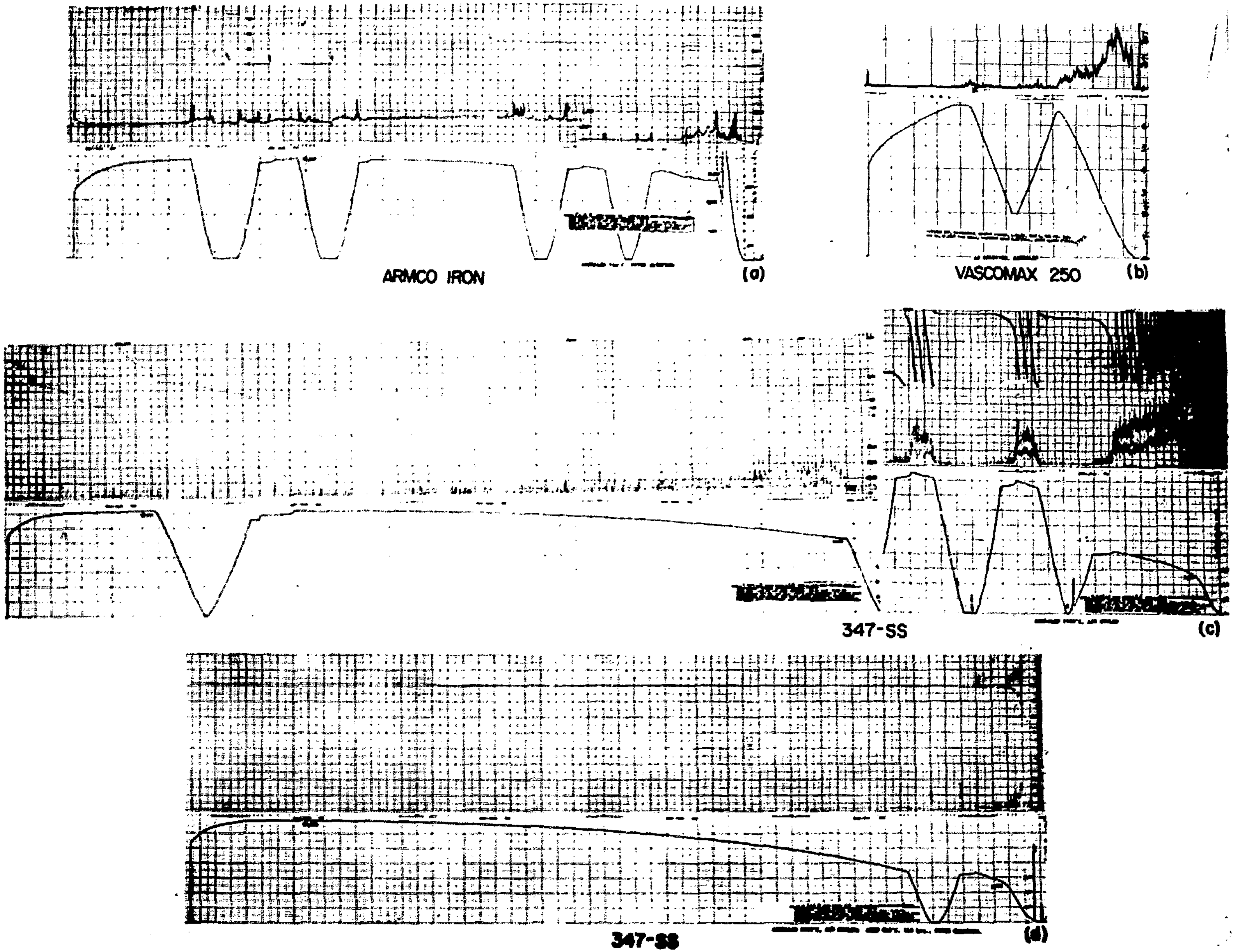


Fig. D8 - Effect of Cycling. Alloys of Iron (a), Annealed Soft Vascomax-250 (b), and 347 Stainless Steel (c and d). Samples Cycled to a Load Higher than the Previous One to Initiate Additional Acoustic Emission.

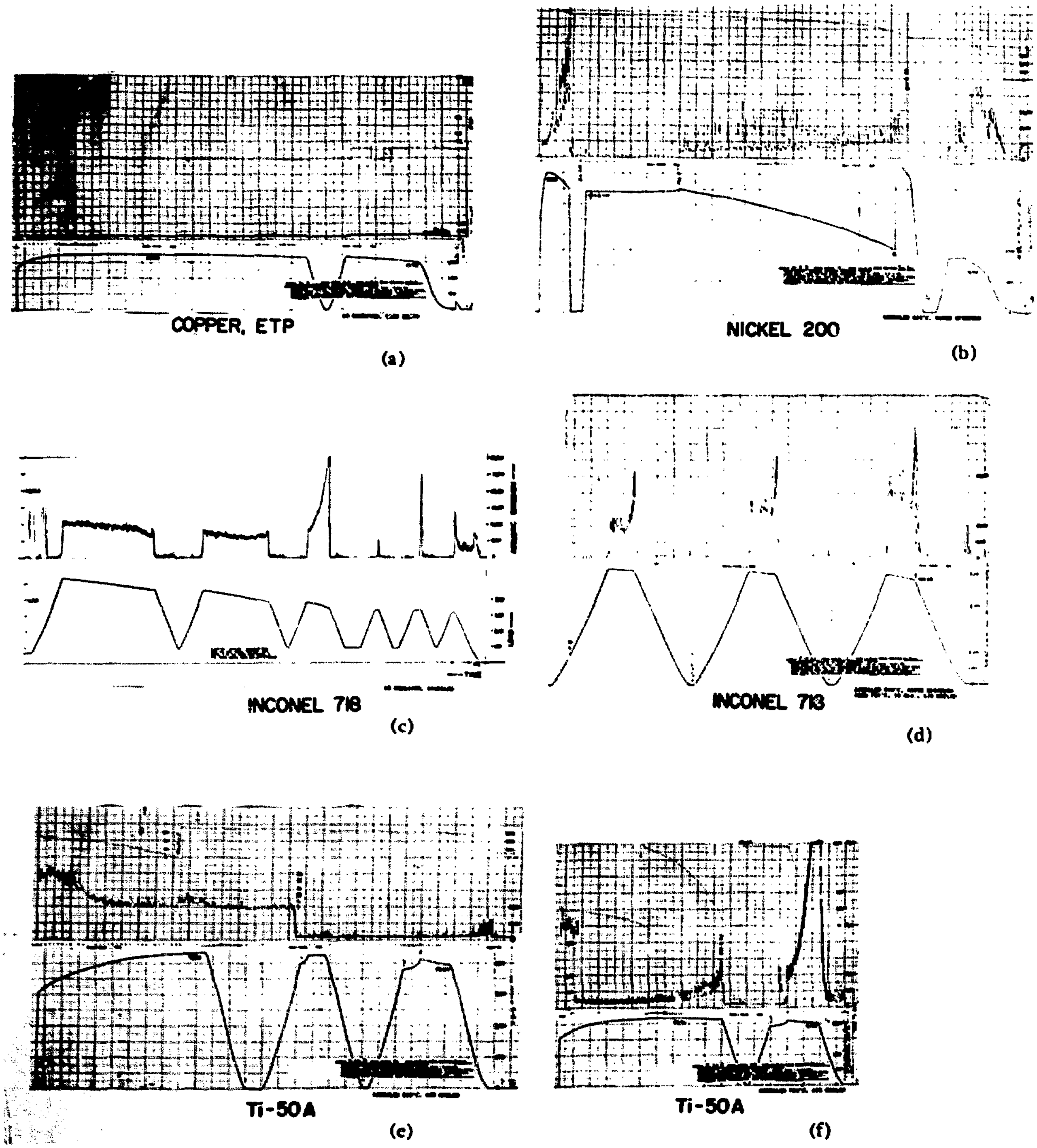


Fig. D9 - Effect of Cycling. Alloys of Copper (a), Nickel-200 (b), Inconel-718 (c and d) and Titanium (e and f). Samples Cycled to a Load Higher than the Previous One to Initiate More Acoustic Emission. Note the Arrows Pointing to Unload Emissions.

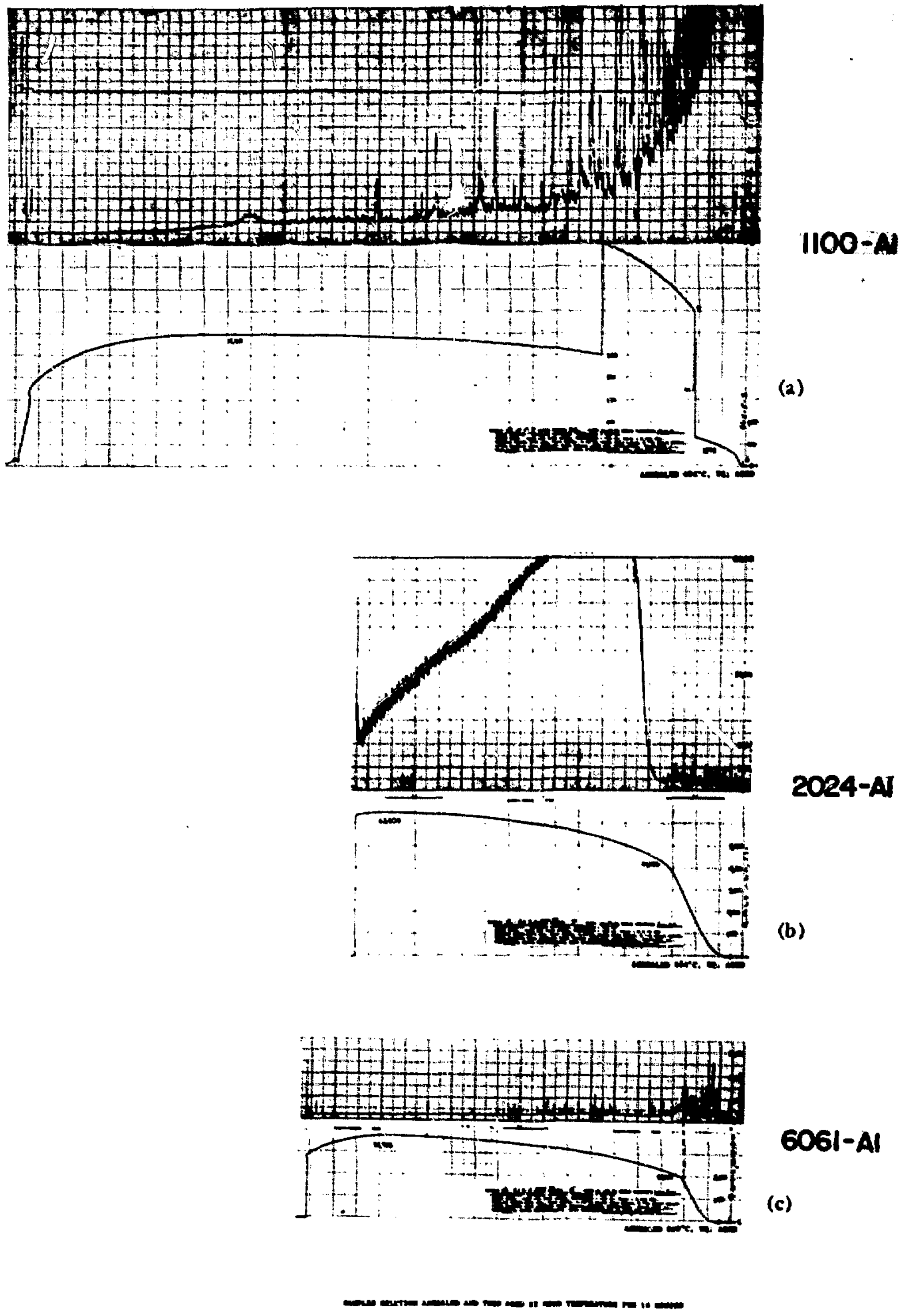
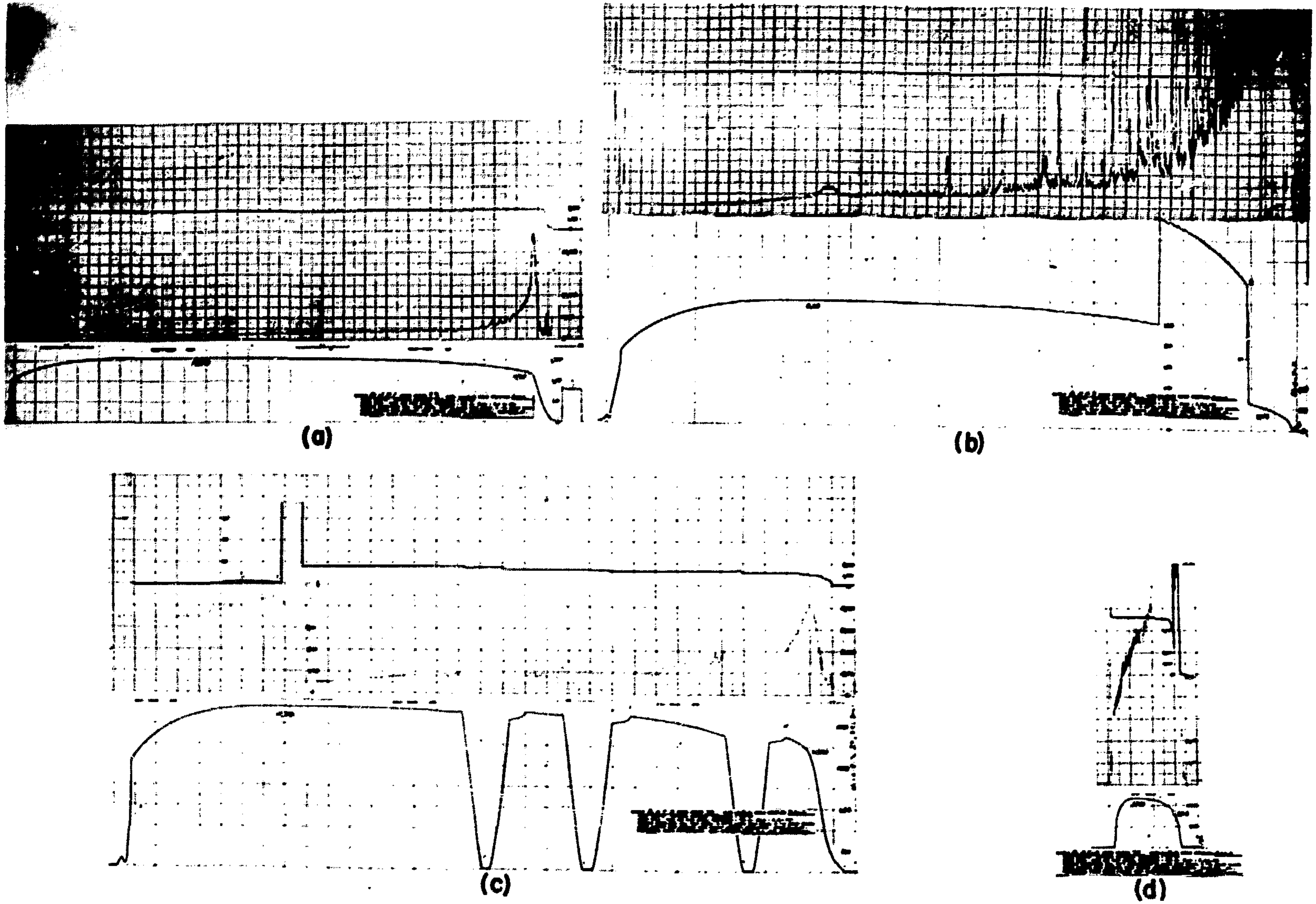
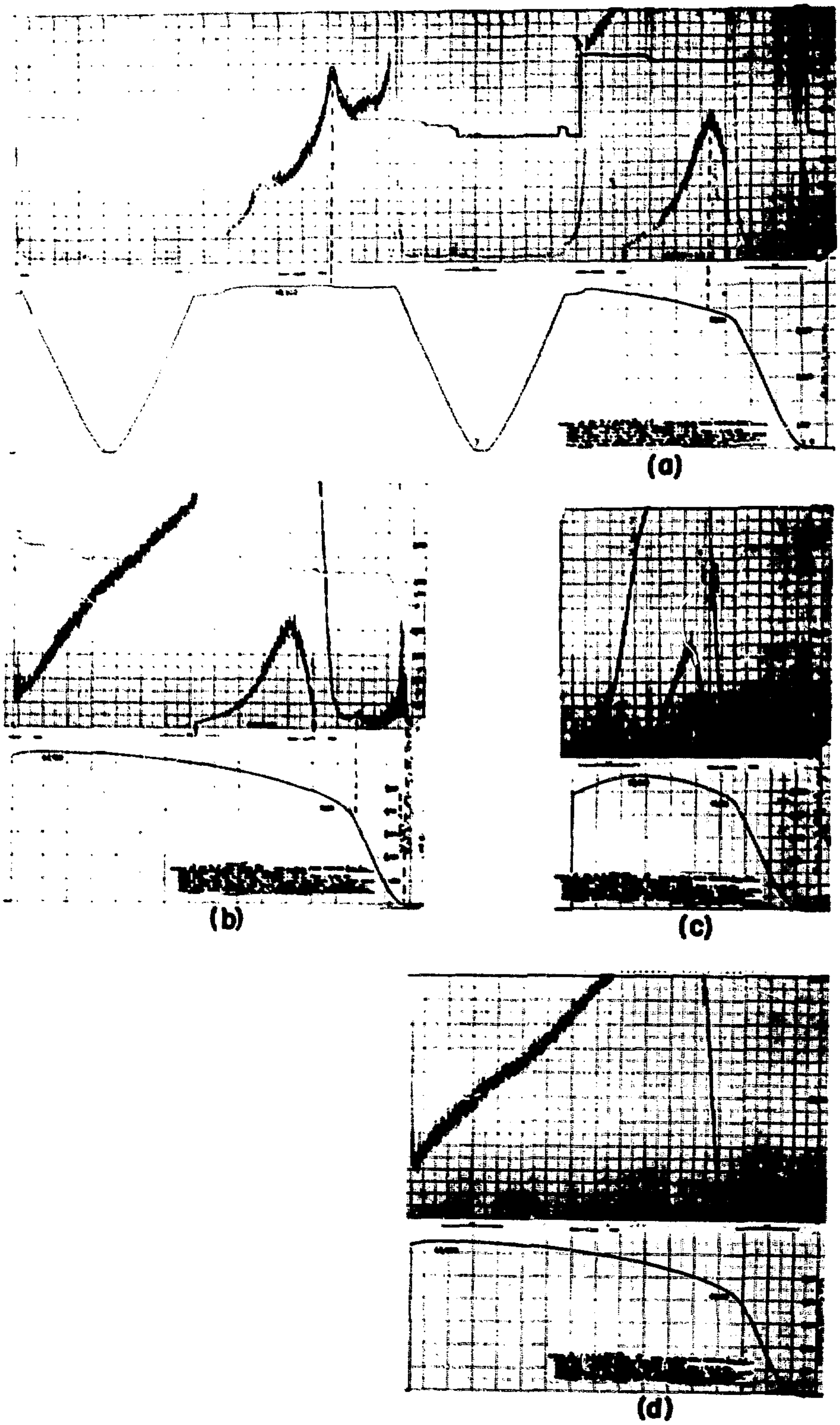


Fig. D10 - Comparison of Types 1100 (a), 2024 (b), and 6061 (c) Aluminum Alloys in the Solution Annealed and Natural Aged Condition.



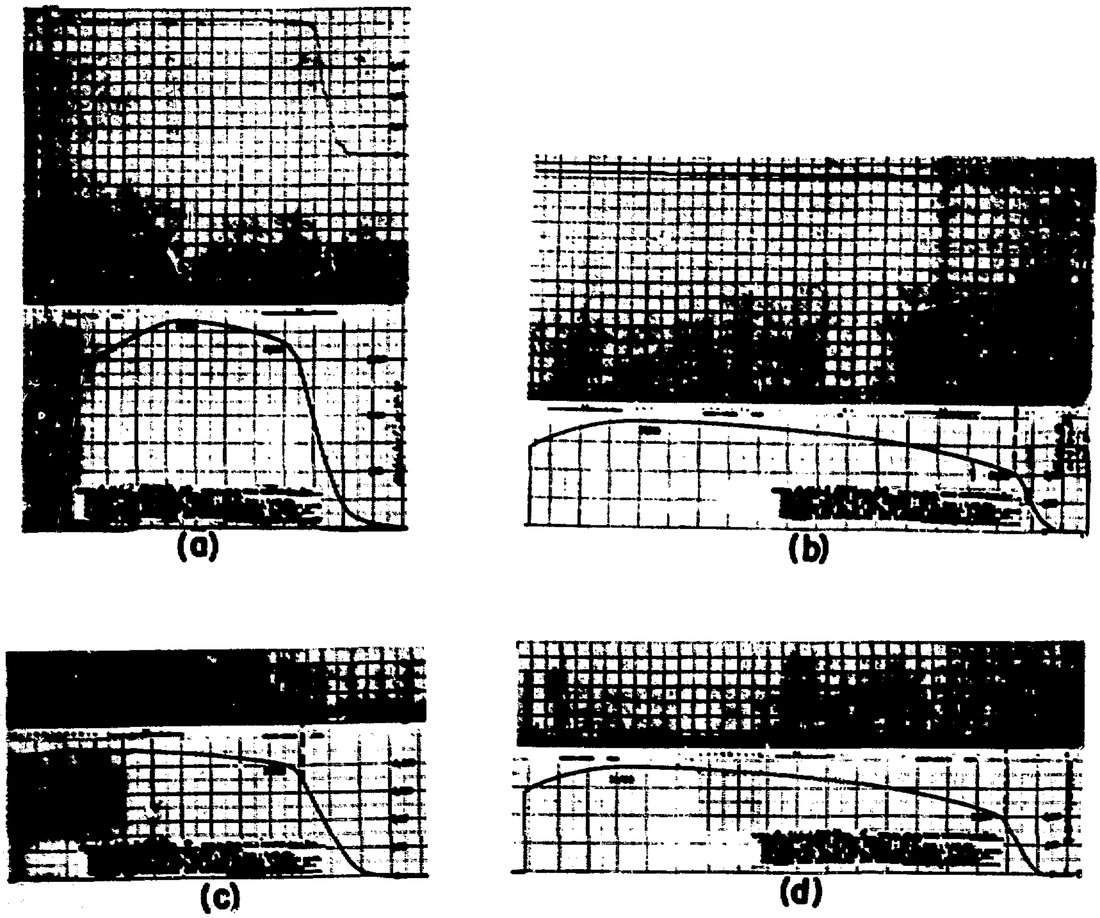
1100-Al

Fig. D11 - Type 1100 Aluminum. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 484°C, WQ and Then Natural Aged, (c) Annealed at 395°C, WQ and Then Natural Aged, and (d) Annealed at 380°C, WQ and Then Natural Aged.



2024-Al

Fig. D12 - Type 2024 Aluminum. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 484°C, WQ and Then Refrigerated at 0°C Until Testing, (c) Annealed at 484°C, WQ and Then Aged at 193°C, and (d) Annealed at 484°C, WQ and Then Natural Aged.



6061-Al

Fig. D13 - Type 6061 Aluminum. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 530°C, Slow WQ and Then Refrigerated at 0°C Until Testing, (c) Annealed at 530°C, Slow WQ and Then Aged at 160°C, and (d) Annealed at 530°C, Slow WQ and Then Natural Aged.

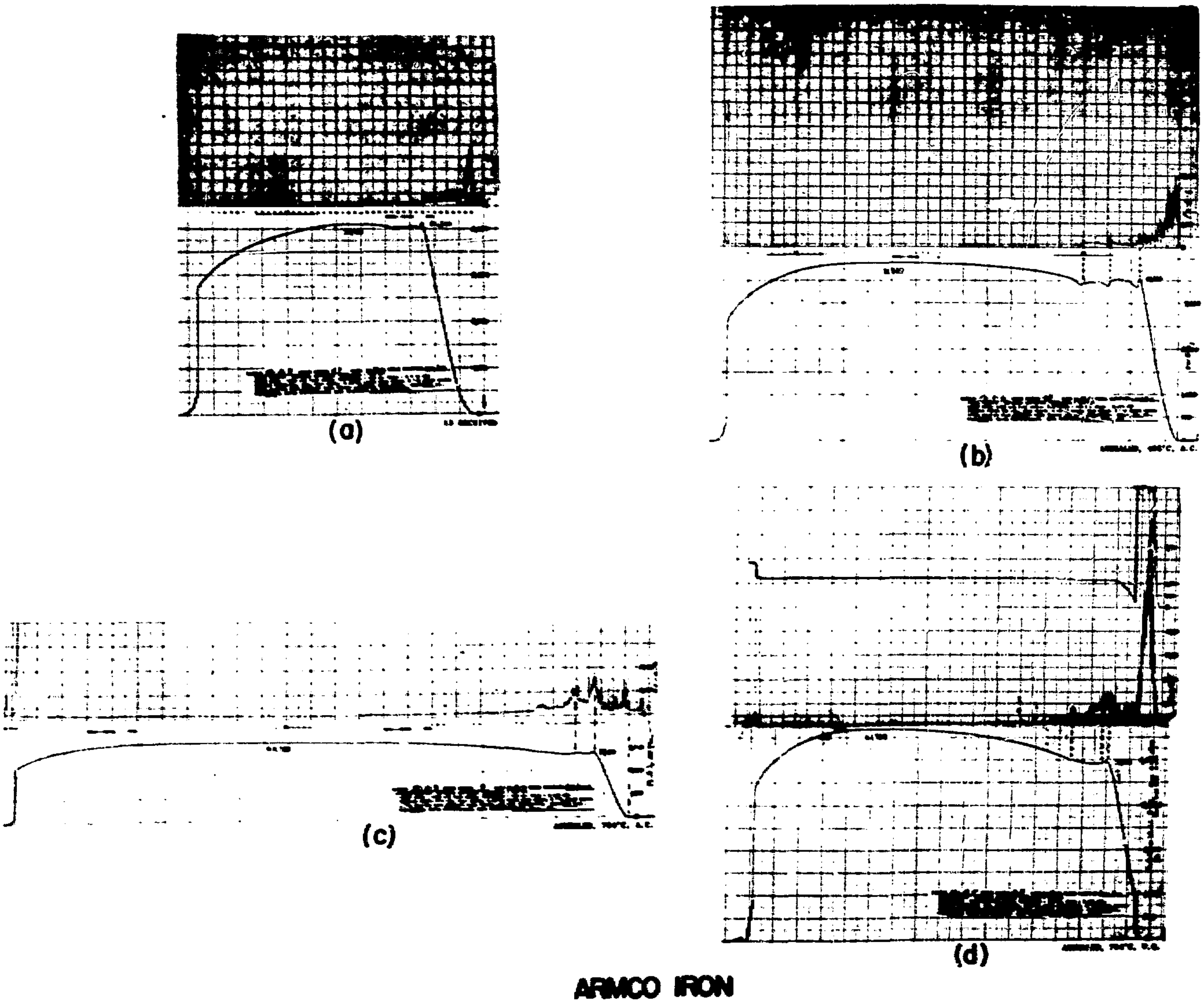
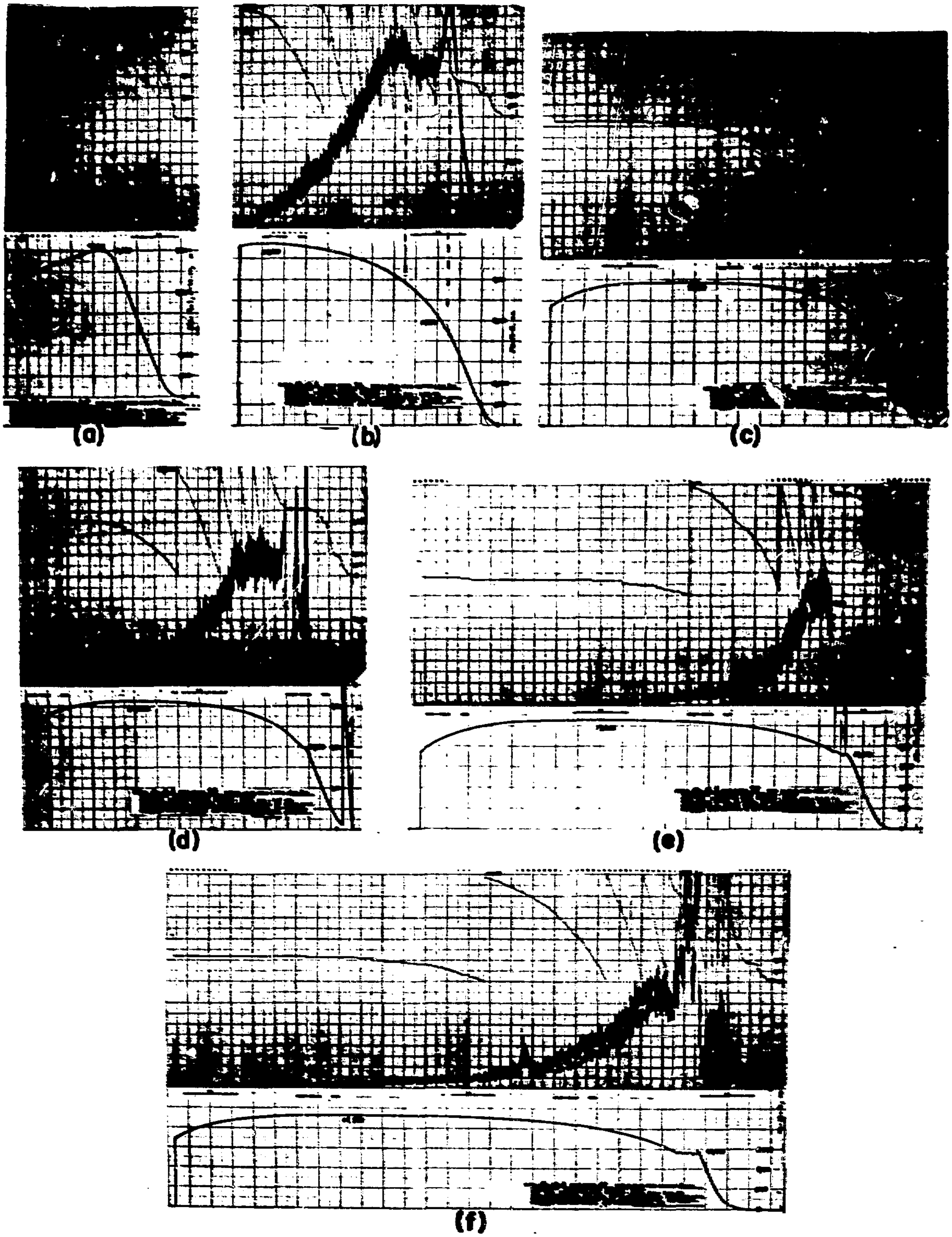
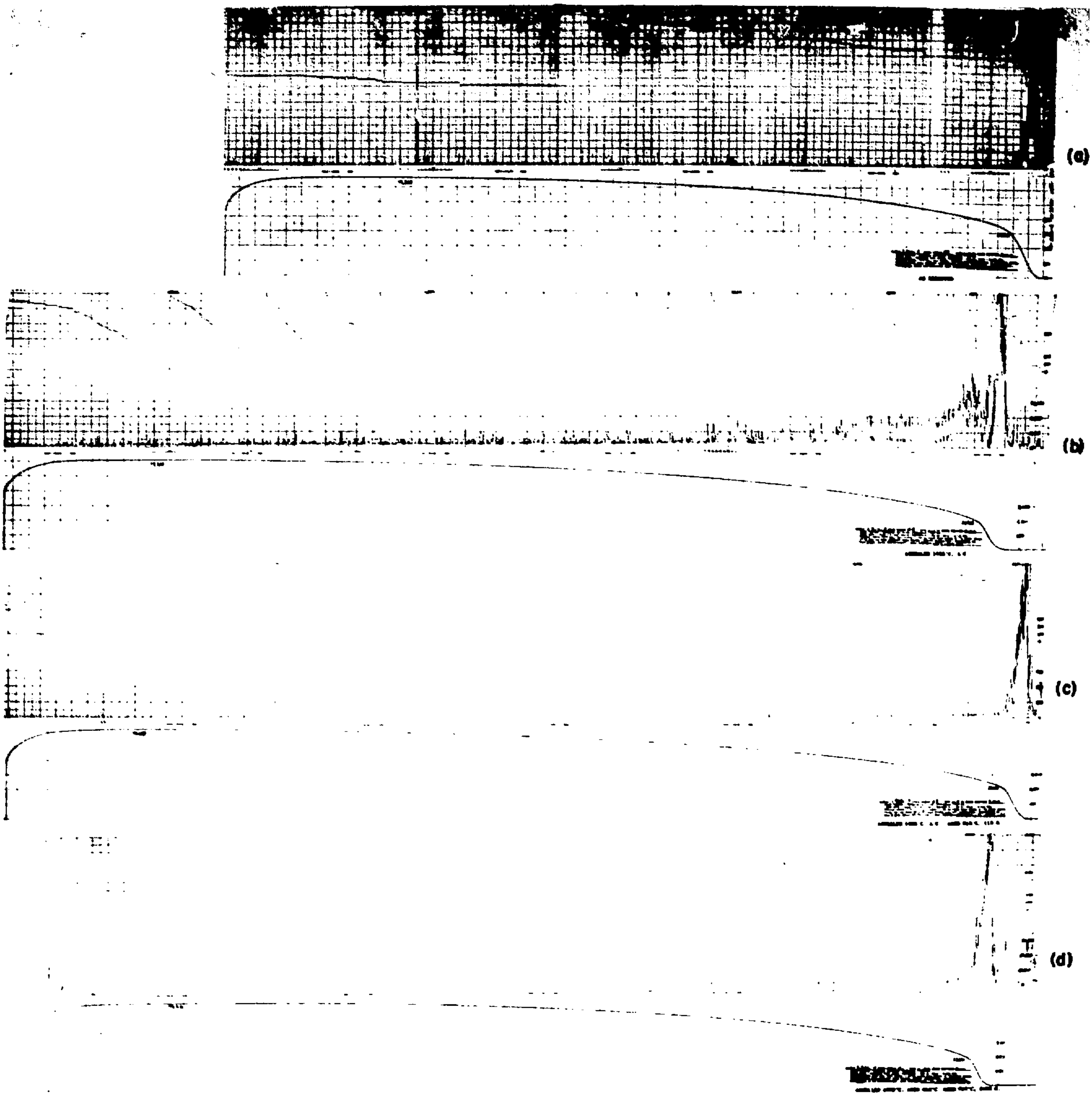


Fig. D14 - Armco Iron. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 495°C and Air Cooled, (c) Annealed at 704°C and Water Quenched.



SAE 1019

Fig. D15 - Low Carbon Steel, SAE 1019. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 790°C and WQ, (c) Annealed and Then Tempered at 288°C, (d) Annealed and Then Tempered at 429°C, (e) Annealed and Then Tempered at 594°C, (f) Annealed at 790°C and Air Cooled.



304L-SS

Fig. D16 - Type 304L Stainless Steel. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 1085°C and Air Cooled, and (c) Annealed at 1085°C, AC and Then "Overaged" at 729°C for 2190 Hours.

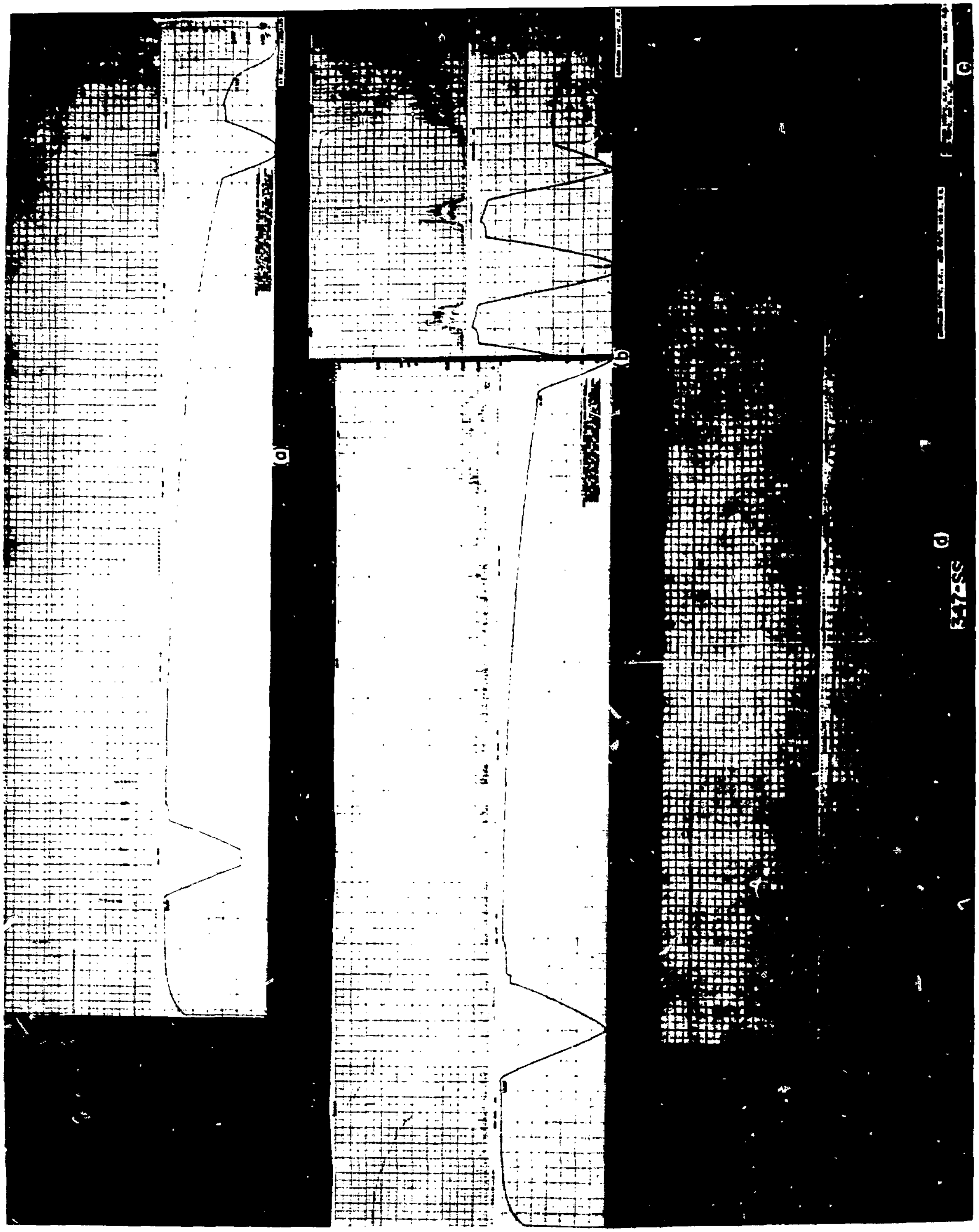


Fig. D17 - Type 347 Stainless Steel. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 1085°C and Air Cooled, and (c) Annealed at 1084°C, AC and Then "Overaged" at 815°C for 115 Hours.

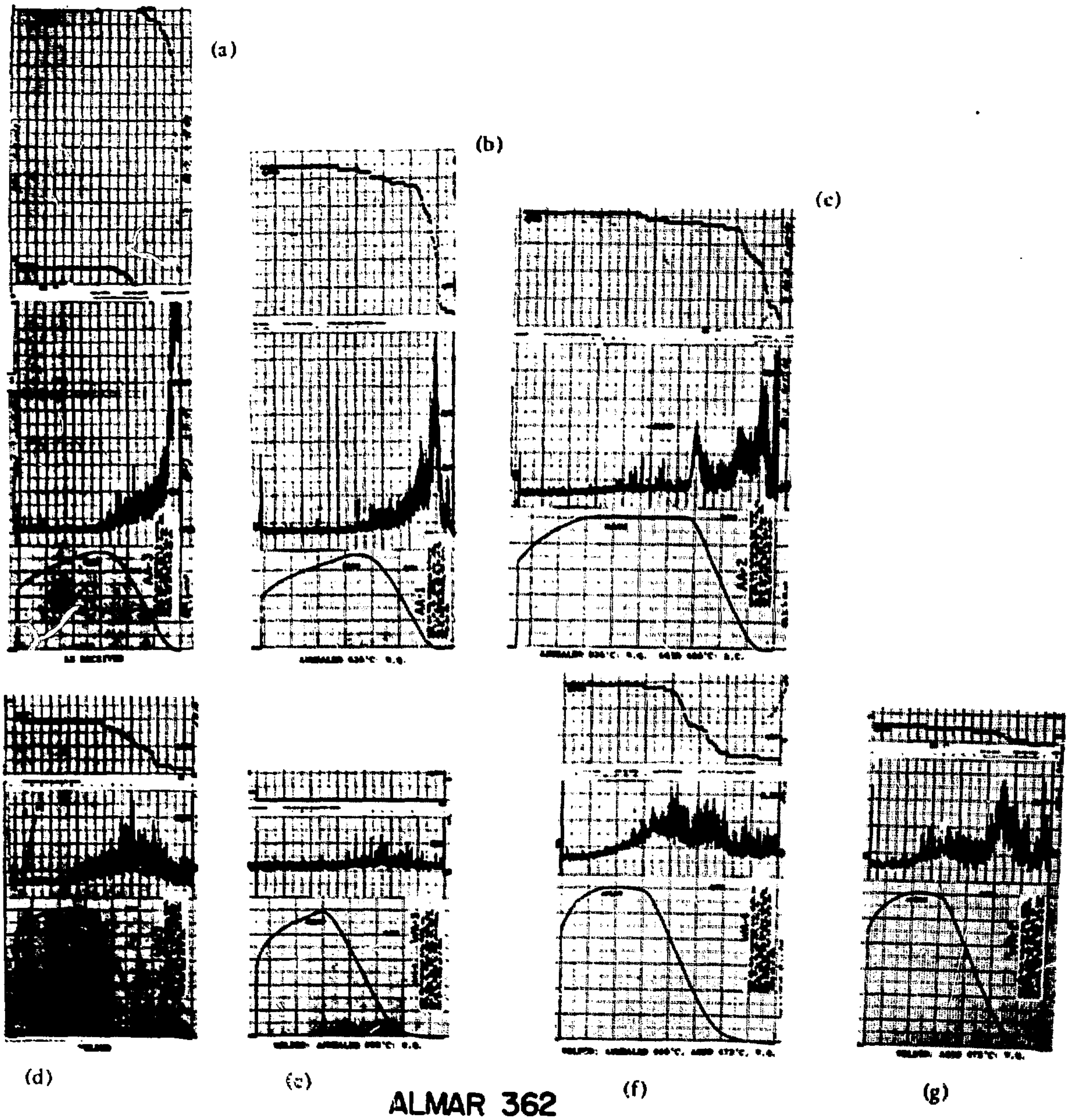
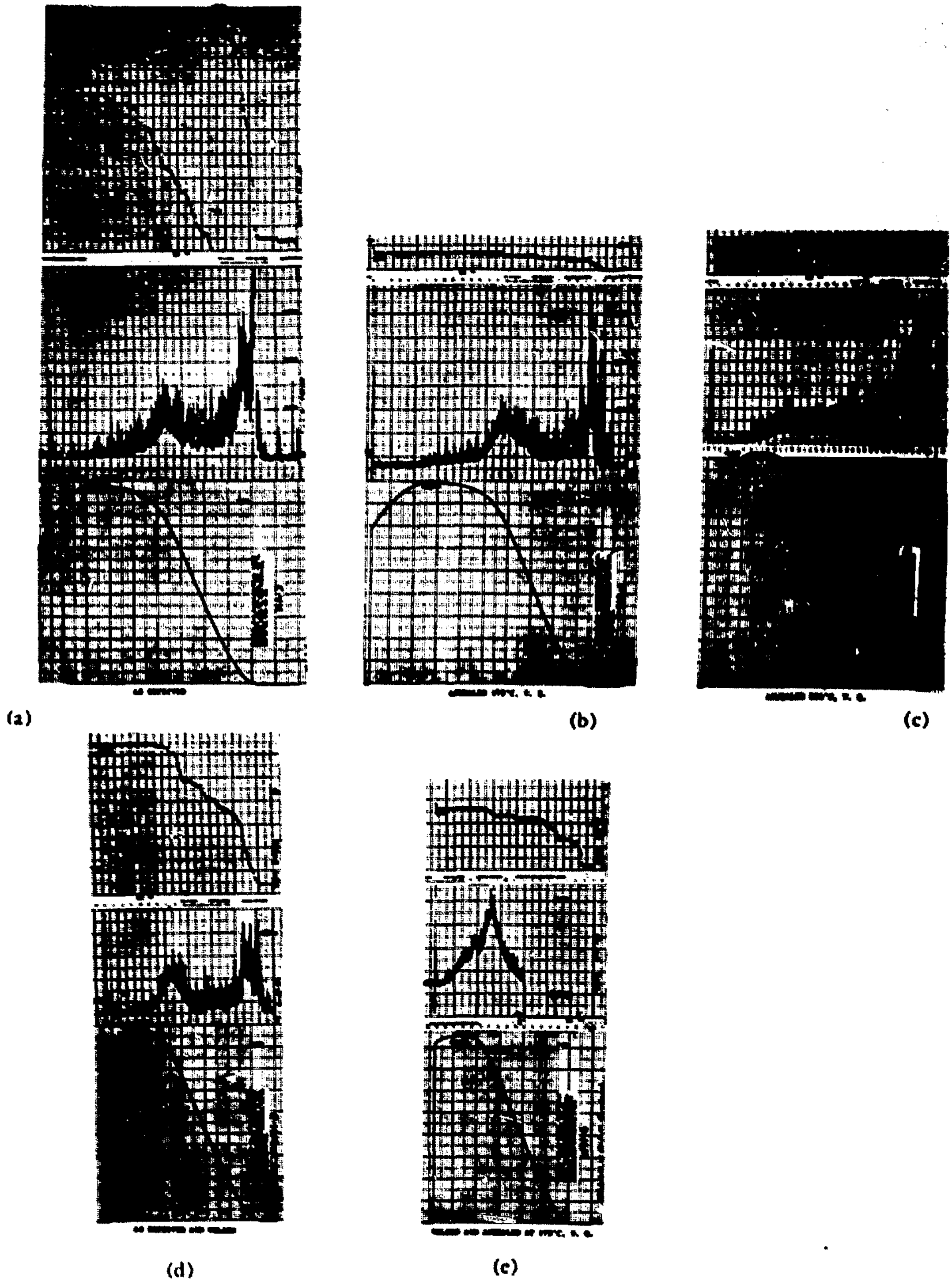
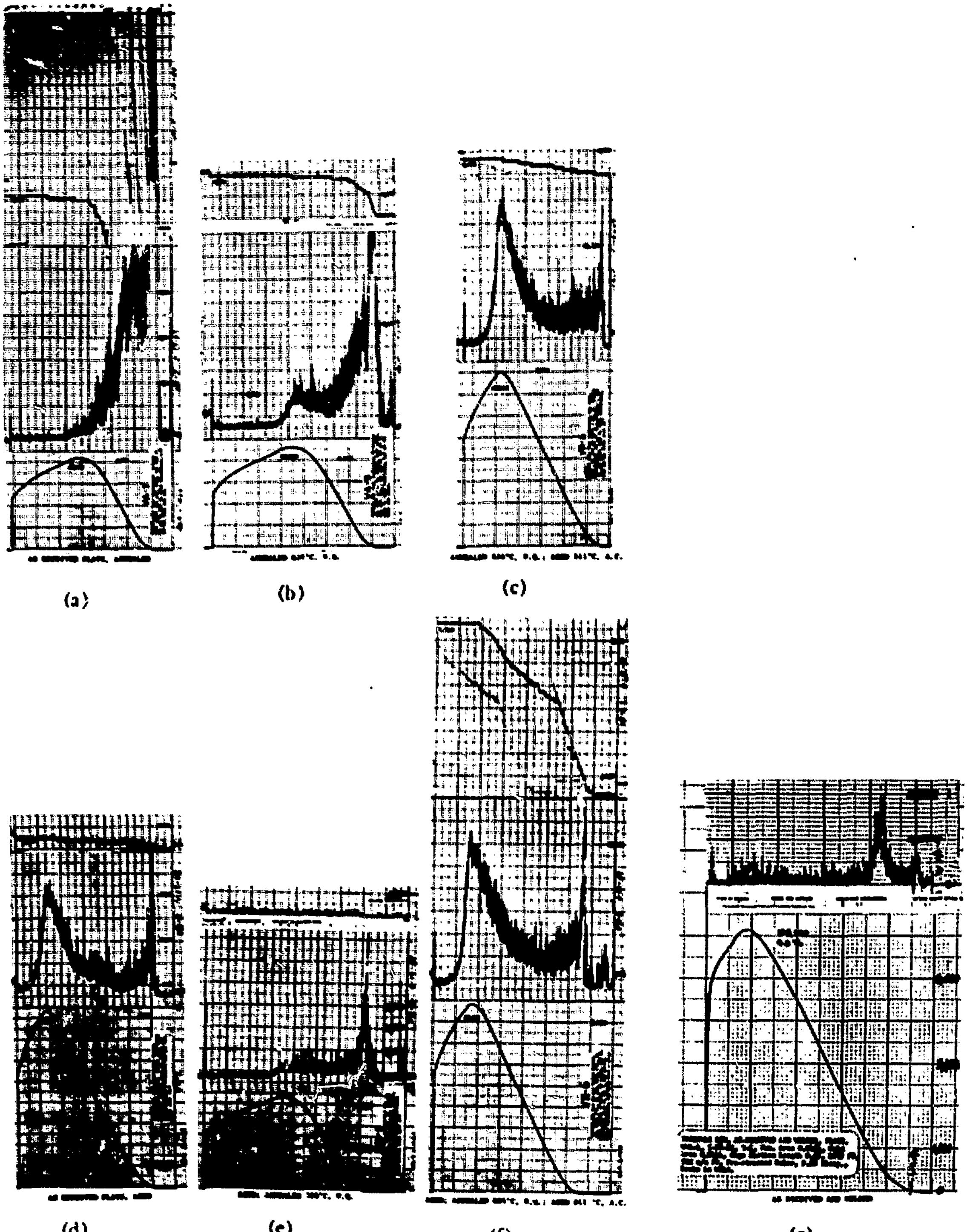


Fig. D18 - Almar-362. Illustrates the As-Received Material (a) and the Effect of Annealing at 835°C and WQ (b), and of Annealing Plus Aging at 488°C (c). As-Welded Material is Shown in (d) and Further in the Annealed at 888°C Condition (e), the Annealed and Aged at 472°C Condition (f), and Finally in the Aged Only Condition (g).



HP-9-4-20

Fig. D19 - HP-9-4-20. Illustrates the As-Received Material (a) and the Effect of Annealing at 835°C and Water Quenching (b), and of Aging at 472°C and Water Quenching (c). Also Shown is the Effect of Welding (d) and of Aging the Weld at 472°C (e).

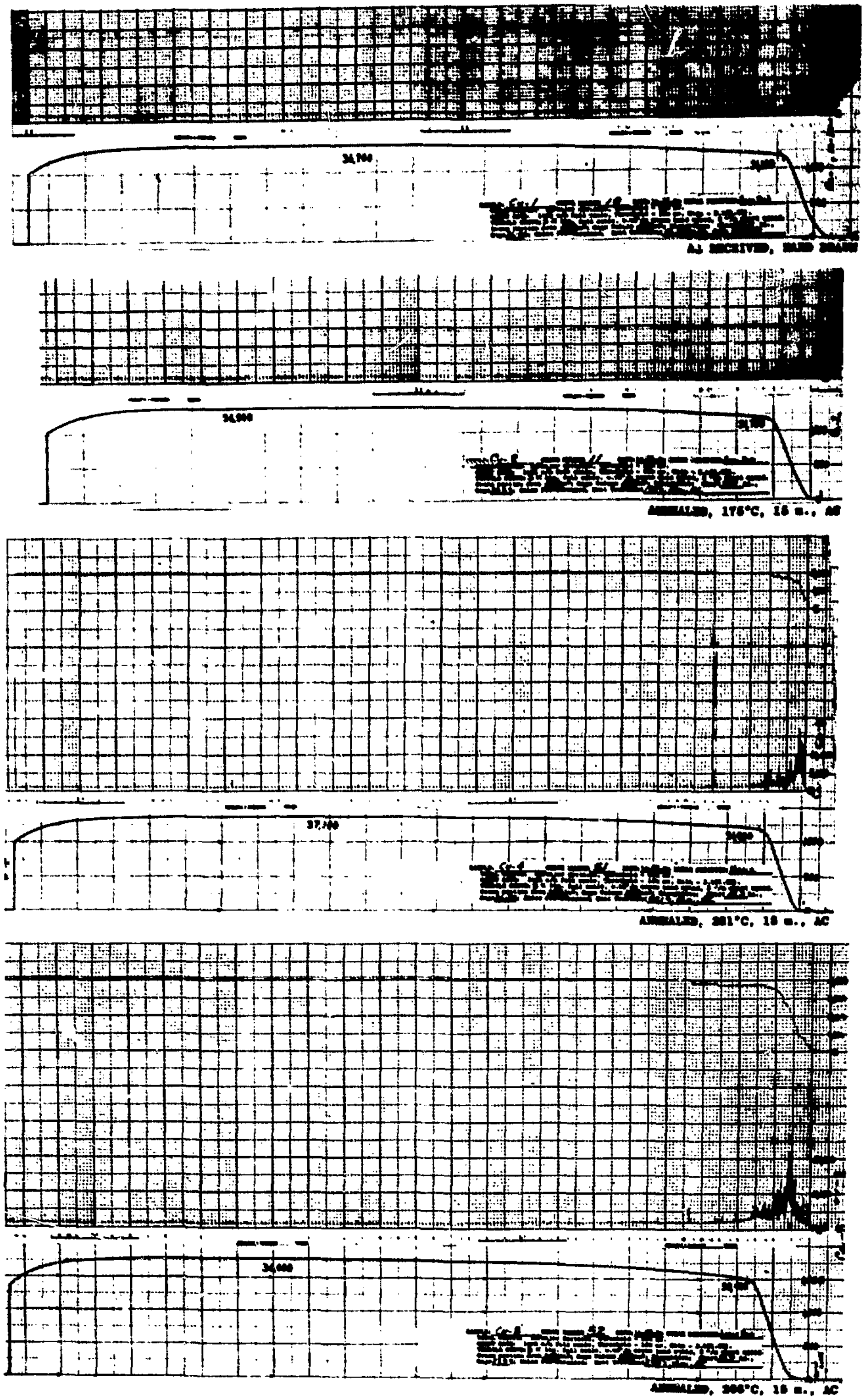


(a) (b) (c)

(d) (e) (f) (g)

VASCOMAX 250

Fig. D20 - Vascomax-250. Illustrates As-Received Material in the Annealed Condition (a), the Effect of Annealing at 835°C and WQ (b), and the Effect of Annealing at 835°C and Then Aging at 511°C (c). Also Shown is As-Received Material in the Aged Condition (d), the Effect of Annealing at 835°C (e), and the Effect of Annealing and Then Aging at 511°C (f). The Influence of Welding is Shown in (g).



(a)

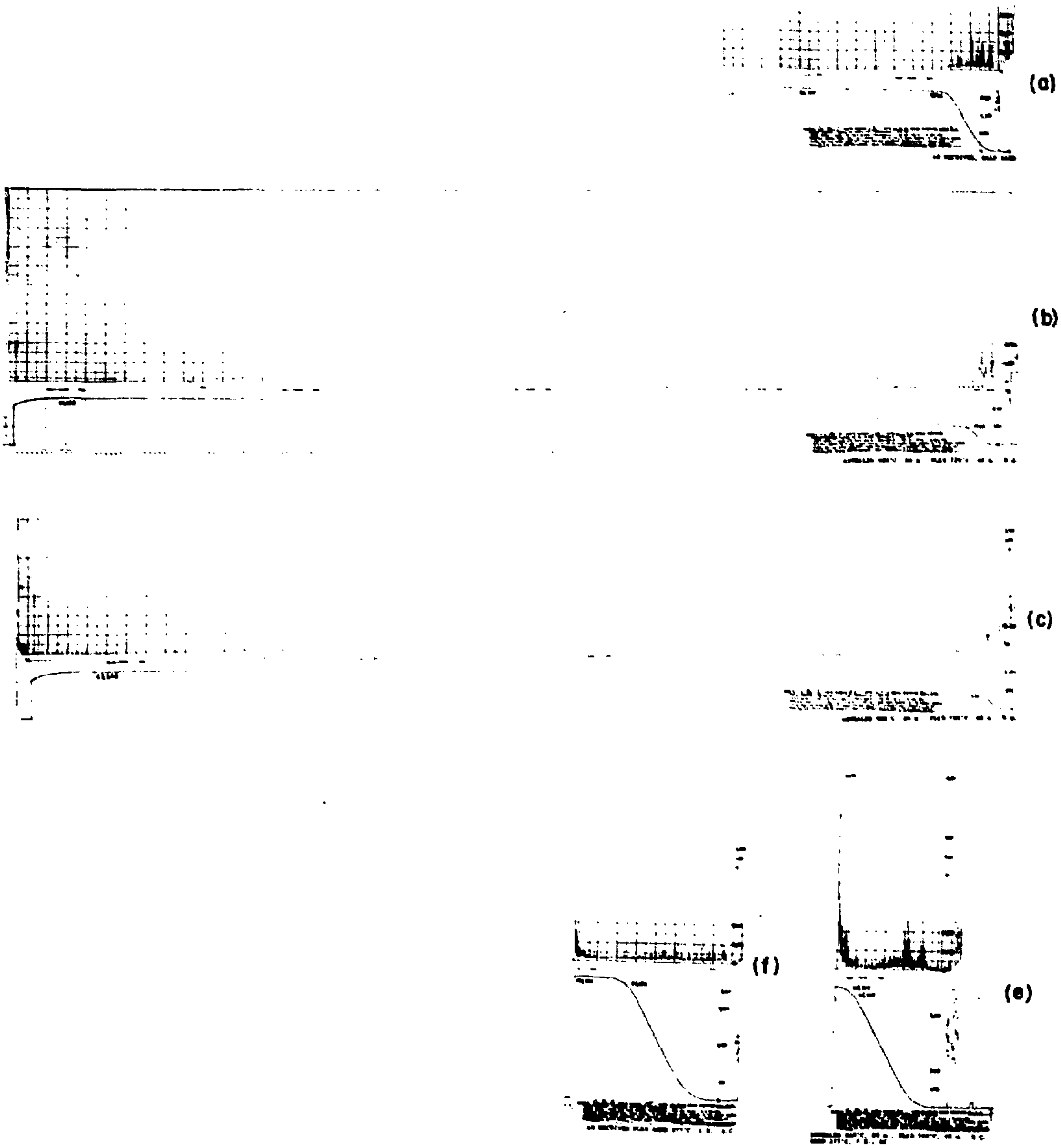
(b)

(c)

(d)

COPPER. ETP

Fig. D21 - Electrolytic Tough Pitch Copper. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 175°C and Air Cooled, (c) Annealed at 221°C and Air Cooled, and (d) Annealed at 288°C and Air Cooled.



BERYLCO-25

Fig. D22 - Berylco-25. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 790°C and Water Quenched, (c) Annealed at 790°C, WQ and Then Aged at 377°C, and (d) Aged at 377°C and Air Cooled.

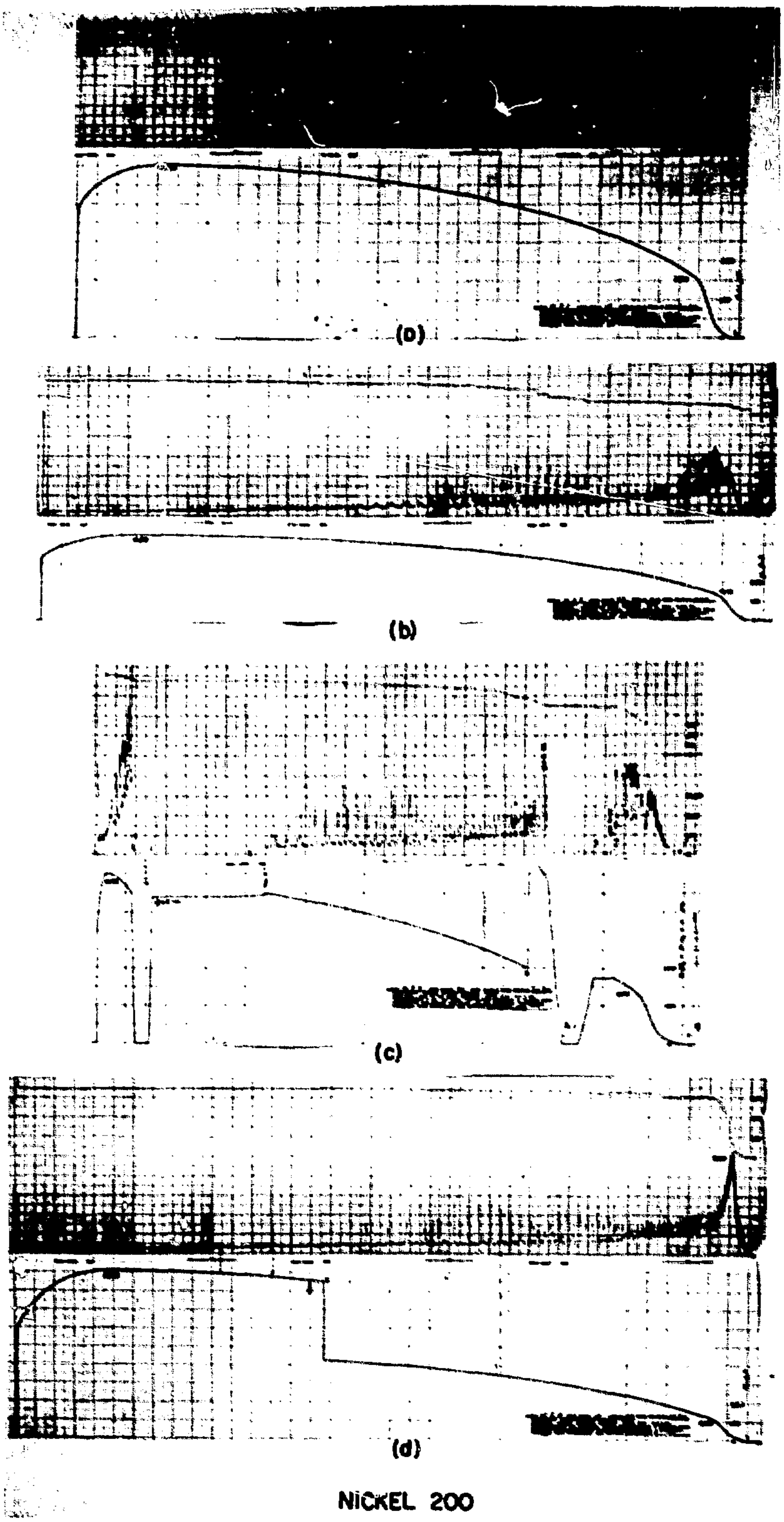
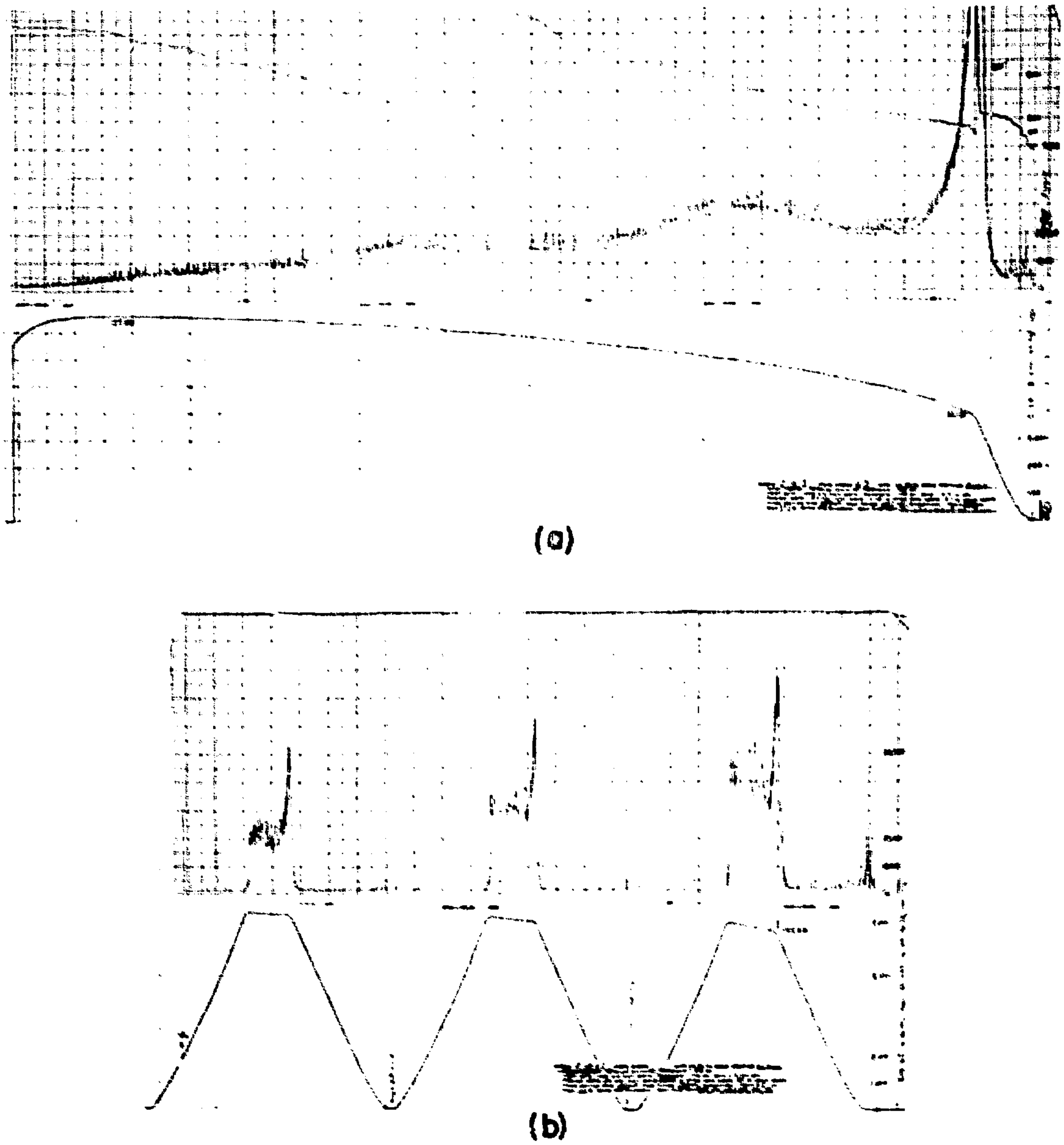


Fig. D23 - Nickel-200. Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 427°C and Water Quenched, (c) Annealed at 534°C and Water Quenched, and (d) Annealed at 760°C and Water Quenched.



INCONEL 718

Fig. D24 - Inconel-718. Illustrates the Influence of Annealing at 980°C and Water Quenching (a) and of Annealing and Then Aging at 721°C (b).

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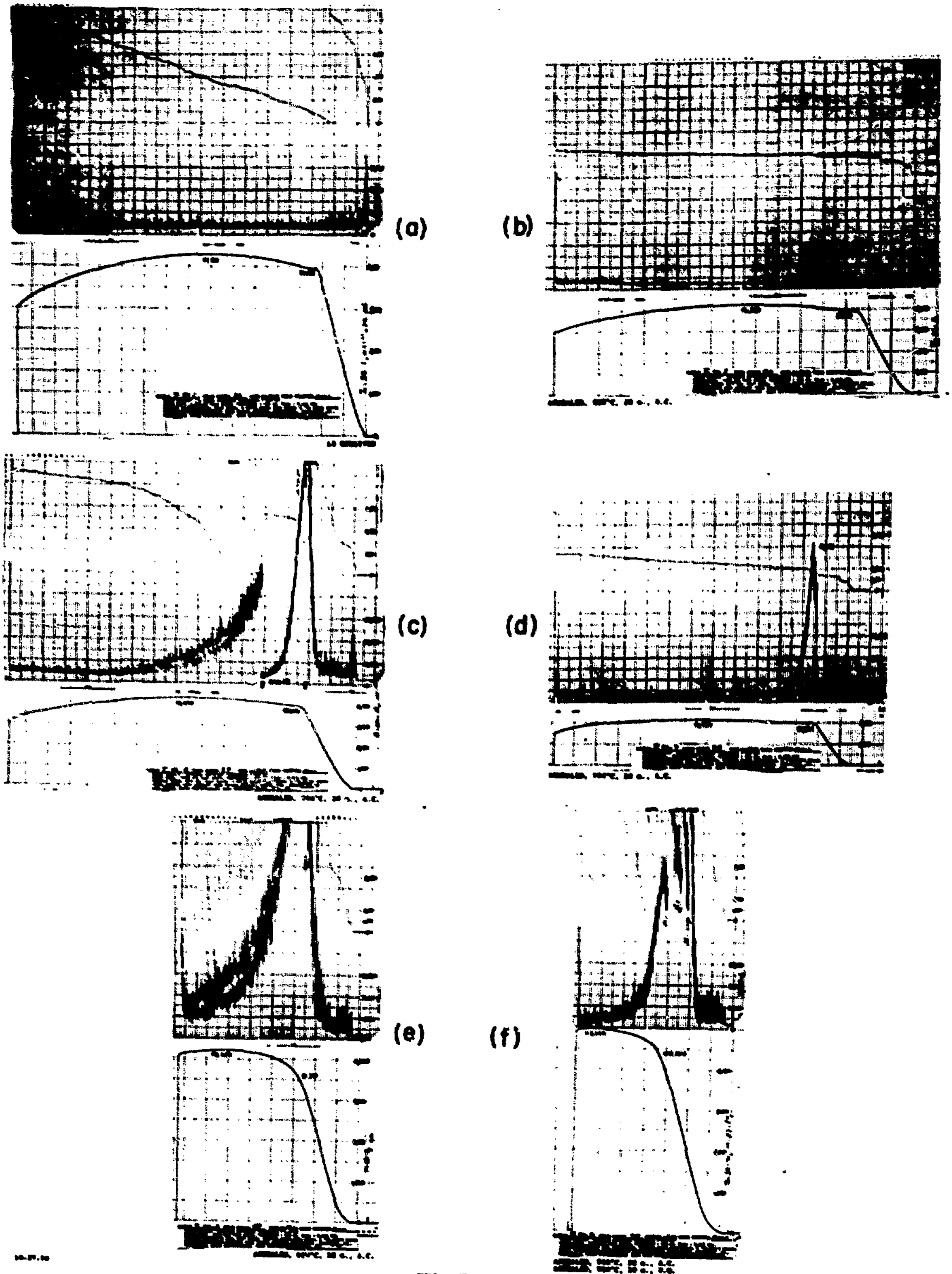

Ti-50A

Fig. D25 - Titanium (Ti-50A). Illustrates the As-Received Material (a) and the Effect of Heat Treatment, (b) Annealed at 539°C and Air Cooled, (c) Annealed at 704°C and Air Cooled, (d) Annealed at 959°C and Air Cooled, and (e) Annealed at 960°C and Water Quenched.