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QUANTITATIVE MEASUREMENTS OF PHASE TRANSFORMATION KINETICS IN LOW ALLOY STEELS DURING PROGRAMMED COOLING

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QUANTITATIVE MEASUREMENTS OF PHASE TRANSFORMATION KINETICS IN LOW ALLOY STEELS DURING PROGRAMMED COOLING

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ABSTRACT

The transformation kinetics during the programmed cooling of several low alloy steels in wire form were studied using a magnetic permeability method. The specimens, in the core of an inductor coil, were cooled from the austenitizing temperature along a number of different programmed cooling paths. In this type of measurement, as the austenite decomposes, the permeability increases which in turn changes the resonant frequency of the inductor coil circuit. The period of the inductor coil circuit was continuously recorded providing a sensitive record of the transformation kinetics. Continuous cooling transformation diagrams determined in this manner for AISI 4340 and AMS 6416 (300-M) were compared with published diagrams. Certain time-temperature paths for these alloys resulted in the retention of large amounts of austenite at room temperature.

I. INTRODUCTION

Continuous cooling transformation (CCT) diagrams are important aids in the control of the microstructure during heat treatment. The microstructures resulting from the heat treatment determine the properties of the alloy. Moreover, composition dependence of microstructure will also affect the mechanical properties. The extent to which alloying elements influence properties is not yet predictable and must be determined experimentally. The influence of different time-temperature paths on the decomposition of austenite may be predicted from an experimentally determined CCT diagram.

Some tempered martensitic steels show poor bainitic hardenability. As a consequence, the microstructure and therefore the properties are likely to vary widely with section size. For such steel it is critical therefore to know the positions of the pearlite and bainite noses on the CCT diagram. The purpose of this investigation was to investigate the effects of programmed cooling on the transformation kinetics using a magnetic permeability method (MPM). The MPM proved to be a sensitive as well as a convenient means of monitoring the austenite decomposition.

Other investigators have studied phase transformations during continuous cooling by following a physical property that changes during the transformation. These methods include a) hardness measurements along the length of an interrupted end quench bar,[1] b) observation of microstructure along the length of an end quench bar[2] or of specimens withdrawn from a gradient furnance,[3] c) thermal analysis,[4] d) combination of thermal analysis and dilatometry,[5,6] e) electrical resistance,[7]

f) combination of dilatometry and metallography,[8] and g) magnetic permeability.[9] Several of these techniques have obvious drawbacks. Quantitative metallography is slow and tedious and requires skillful interpretations of micrographs.[10] Dilatometric measurements are hampered by the difference in thermal expansion of the ferrite plates and austenite.[10] Hardness and electrical resistivity measurements are not only a function of the transformation, but they are sensitive to particle size and lattice coherency.[11]

A great deal of effort has been spent on developing techniques that would facilitate the measurements of transformation kinetics. A few investigators have used magnetic permeability techniques. These involved placing the sample in the core of an electrical transformer.[9,12] As the austenite transformed, the magnetic permeability increased thereby inducing an e.m.f. in a secondary coil. In the present study a more sensitive version of the magnetic permeability method[13] was used to measure the transformation kinetics during programmed cooling.

II. EXPERIMENTAL PROCEDURE

A. Material Preparation

The low alloy steels used in the investigation were AISI 4340 and AMS 6416 (300-M). They were received as 5/8 in. thick by 2.5 in. wide bar stock in the fully annealed condition. Their chemical compositions are given in Table I. One inch wide blocks formed from the bar stock were cold rolled to approximately 1/8 in. thick, 8 in. long, and 3 in. wide. These 1/8 in. thick plates were placed in a salt bath for 5 hours at 650°C for stress relief. The plates were then sheared lengthwise into 1/8 in. square rods about 8 in. long. The edges were ground off to produce rods which were swaged down to approximately 0.040 in. in diameter. The wires were then drawn through dies to produce a smooth finish with a final diameter of 0.0358 in.

B. Experimental Apparatus

The transformation kinetics in low alloy steels were measured by monitoring the change in the magnetic permeability as the specimens transformed from austenite. There is a large difference in magnetic permeability between austenite and any of the transformation products while the difference in magnetic permeability is smaller for the transformation products. The MPM provided a convenient, rapid and sensitive measurement of the transformation kinetics during programmed cooling. The continuous cooling system is shown in Fig. 1.

The experimental apparatus consisted of two parts, one for measuring the magnetic permeability and the other for programming the cooling. The MPM[13] was comprised of measuring the permeability and is shown schematically in Fig. 2. A wire specimen of 0.0358 in. diameter and 18 in. in length was suspended in a hollow quartz tube, 2 feet long and 3/4 in O.D. A vacuum of 5.10^{-5} microns or better was obtained before the specimen was heated by resistance to an austenitization temperature of 870°C for 8 minutes. The inductor coil, which was 5 in. long and 1 in. I.D., was placed coaxially around the quartz tube. As the wire cooled at a predetermined rate, the permeability of the specimen increased as the austenite decomposed. This increased the inductance of the coil which caused the resonant frequency of the coil to change. The frequency of oscillation was determined with a variable frequency oscillator (VFO) which operates at approximately 1.2 khz. A cycle counter divided the output VFO by 1600. A control timing decoder unit, which was activated every 1600 cycles of the cycle counter, commanded a time interval counter unit to: (a) reset, (b) start count at 0000, and (c) stop count at approximately 1100 cycles of the cycle counter. At 1100 counted cycles the control timing decoder unit started a paper tape punch unit to record the average period during the preceeding 1100 cycles. Between 1100 and 1600 cycles, the tape was punched and the control timing decoder unit was reset.

After the paper tape was interpreted through the teletype, the typed record consisted of a six digit number. The first digit was used for punch frequency control (i.e. which could be varied), and the

last 5 numbers represented the most significant places in a 9 digit number. The four unrecorded digits were 0008, which were identical in all runs and were therefore not recorded. For example if the six numbers were 904021, the period of oscillation of the coil was 0.000804021 seconds/cycle. The real elaped time between punches was (0.000804021)× (1100) or about 0.88 seconds.

The block diagram of the electronics for the programmed cooling is shown in Fig. 3. A D.C. power source was regulated with a temperature controller. The temperature of the wire was measured with a chromel-alumel thermocouple spot welded on the wire specimen. The thermocouple was connected to the temperature controller and a strip chart recorder. Cooling paths were scribed on a 12 in. by 13 $\frac{1}{2}$ in. sheet of metallized mylar. This sheet was placed on the rotating drum of the Data Trak. A curve follower in the Data Trak controlled a voltage from the Data Trak which was added to the thermocouple voltage. The temperature controller sensed the increase in potential provided by the Data Trak which it interpreted as an increase in potential from the thermocouple junction. Consequently, the output from the power source decreased. The magnitude of the voltage varied with the programmed cooling path. Different cooling paths were obtained by changing the drum rotation rate or by scribing a different cooling path on a new sheet of metallized mylar.

C. Experimental Technique

The ends of the 18 in. specimens were formed into hooks. For convenience in assembly, it was found helpful to make the hook attached to the left support a special shape (denoted as formed hook) shown in Fig. 4. Teflon coated chromel-alumel thermocouples of 0.005 diameter were used to determine the temperature of the wire. The junction was located about 6 in. from the formed hook. The bare ends of the thermocouple were rolled down to about 0.001 in. and were spot welded on the specimen. Ceramic beads protected the length of the thermocouple from the heated specimen. If the two thermocouple wires were offset from one another along the axis of the specimen, an additional potential was imposed on the thermocouple circuit when the heating current flowed through the wire. Consequently, the two wires were attached together on the specimen. An illustration of the specimen thermocouple configuration is shown in Fig. 4. Prior to use, the thermocouple circuit was tested by increasing the sensitivity of the strip chart recorder and passing a current through the specimen for a short time taking care not to heat the specimen above 100°C. If the thermocouples were spot welded incorrectly, a sudden jog was present in the time-temperature trace when the heating current was turned off suddenly.[14] Figure 5 shows examples of time-temperature traces from tests on thermocouple circuits that were considered acceptable, marginal, and unacceptable. Unacceptable junctions were removed and new junctions were made on a different area of the specimen. Cleaning the surfaces with

acetone and a spot welder set at 4.5 watt-sec produced satisfactory welds.

The procedure used to place the specimen into the continuous cooling apparatus is outlined below.

i) The plain hook was attached to the extendable support rod on the right and cap end the coiled heating current lead was connected, Fig. 6.

ii) The specimen was pushed through the quartz tube from the right side until the formed hook could be attached to the ceramic insulator at the end of the support rod of the left end cap. The ends of the thermocouple, which were simultaneously pushed through, were soldered on the insulated posts in the left end cap. The heating current lead was attached, Fig. 7.

iii) The entire assembly was moved to the right until the left end cap was seated against the support cylinder and the lock nut was in place. The right side was then locked in place. A slight tension was placed on the specimen by attaching a compression spring to the extendable support rod.

iv) The system was evacuated and when a vacuum of 5.10^{-5} microns or better was obtained, the experiment was started. The position of the specimen ready for the experimental runs is shown in Fig. 8.

The procedure used in obtaining experimental data is as follows:

i) The electronic systems were turned on and allowed to stabilize.

ii) The specimen was heated manually by increasing the current until the austenitizing temperature of 870°C was reached. The temperature controller was switched to "set point" to maintain the austenitizing temperature for 8 minutes.

iii) Three types of cooling were employed: a) gas quench b) partial vacuum cool, c) slow cool. Each type required a different procedure and will be discussed separately.

a) The procedure used in the gas quench was:

1) System was isolated from the vacuum pumps.

2) A fourway switch in the Data Trak was set on "hold" (instead of run). This setting synchronized the strip-chart recorder with the paper tape punch output.

3) The union nut was removed from the 1/4 in. plug on the gas outlet.

4) The paper tape punch was switched to punch at intervals of 0.88 seconds.

5) Simultaneously, the heating current was turned off, the Data Trak switched on, and extra pure helium was flushed through the system.

b) The procedure used in the partial vacuum cool was:

1) Same as steps 1 and 2 of the procedure used in gas quench.

2) A small volume of helium gas was fed into the system. (The quantity of gas fed in was dependent on the desired partial vacuum).

3) The paper tape punch was switched to punch at intervals of 0.88 seconds.

4) The heating current was switched off and the Data Trak switched on simultaneously.

c) The procedure used in the slow cool was:

1) The desired cooling path was scribed on the metallized mylar sheet and wrapped around the rotating drum of the Data Trak. Pins were used to hold the sheet in place. An appropriate drum rotation rate was selected.

2) The paper tape punch was turned on to punch at 0.88 second intervals.

3) The four-way switch in the Data Trak was set on "run" and was switched on.

4) The interval between punches was increased to either 8.8 seconds or 88 seconds depending on the cooling rate.

The entire CCT diagram was constructed from one specimen. This eliminated some of the inevitable variation when several specimens are used for the same CCT diagram. The results from carbon analysis on the specimens showed no decarburization occurred.

D. Temperature-Structure Calibration

The temperature-structure calibration was required to determine the change in the magnetic permeability as a function of temperature, strain, and morphology.[18] The appropriate reference microstructure was selected for the temperature-structure calibration according to the temperature range. This simultaneously accounted for the effects of temperature and structure. A calibration curve was required for each alloy to account for the magnitude of these effects. A fully martensitic structure was used for the range of temperatures below the M_s. For the temperature range between M_s and B_s a fully

bainitic specimen transformed isothermally was substituted. At temperatures above B_s, a fully pearlitic structure was used.

A calibration was performed with fully transformed specimens of the appropriate reference structures. At temperatures below the M_s, the calibration for 4340 and 300-M consisted of gas quenching the austenitized specimen to room temperature. The specimens were held briefly at various temperatures below the M_s and the change in period (ΔP) was recorded.

In 4340 reference structures were needed for ranges between M_s to 500°C and between 500°C to 650°C. For these structures specimens were fully transformed isothermally at 350°C and 650°C. For temperatures between M_s and 500°C, the specimen transformed at 350°C was used as the reference structure for calibration. In the range from 500°C to 650°C, the 650°C specimen was used. The calibration curve for 4340 is shown in Fig. 9.

For the calibration structures of 300-M, the martensitic structure was used to obtain the calibration in the range M_s to 650°C.[15] The calibration curve is shown in Fig. 9.

It was assumed for calibration purposes that the specimens transformed fully to martensite during the gas quench. Although from transmission electron microscopy , it has been shown that traces of retained austenite are present in oil quenched fracture toughness specimens.[19]

E. The Volume Fraction Calibration

The variation of the change in period (ΔP) with the volume transformed was determined by gas quenching specimens of different diameters to room temperature. The diameter of the wire is directly related to the volume by $\pi \times (\text{diameter}/2)^2 \times$ (the length of the wire within the field of the inductor coil). Thus the effect of volume transformed could be determined by merely changing the diameter of the wire. The ΔP was measured for specimen diameters of 0.020, 0.025, 0.030, and 0.035 in.

The relationship between the volume fraction transformed and the change in period, ΔP, was found to be linear, Fig. 10. Therefore the volume fraction transformed at a given time along a cooling path was the ratio of the change in period at that time to the change in period of a fully transformed specimen with the appropriate reference structure.

F. Metallography

Specimens with the desired cooling history were examined by optical metallography. Half inch lengths of wire were cut from the middle of the specimen and were mounted horizontally in Koldmount. They were ground on successively finer silicon carbide papers to 600 grit. This was followed by a polish with a 1 micron diamond paste. Final polishing was done in a solution of distilled water containing 0.05 micron alumina. The polished surfaces were etched with 2% nital for 5-20 seconds.

III. RESULTS AND DISCUSSION

A. Magnetometric Technique

Continuous cooling transformation diagrams were readily constructed using the above described magnetic permeability method. The transformation kinetics were continuously measured while the specimen cooled with a predetermined time-temperature path. The CCT diagrams for 4340 and 300-M are shown in Figs. 11 and 12, respectively. The zero time of the cooling path was taken at the moment the temperature dropped below the austenitization temperature. Some investigators have considered the start of the cooling path when the A_{c_3} temperature was reached. The disadvantage of choosing this criterion as the start time is that this does not permit the direct comparison of diagrams for steels that have different critical temperatures.[2]

Conventionally the M_s has been defined as the temperature at which only one percent of the austenite transforms athermally to martensite. Using the MPM, greater accuracy of definition is possible. By the use of MPM the start of the transformations could be detected in amounts as small as 0.1% of martensite. The M_s in this study was taken as 0.1% of transformation. The start of transformation for the other transformation products was also taken as 0.1%.

A limitation of the MPM was encountered in cooling paths that produce two or three different structures. For example, it was difficult to determine the M_s for both 4340 and 300-M for cooling paths that passed through the bainite nose. For such cases the M_s

can be determined by thermal analysis for a few cooling paths.[4,6] For cooling paths labeled 1H and 1I (Fig. 11) in 4340, the M_s was undeterminable by MPM, but the M_s could be detected by MPM for cooling path 1J. The broken line in Fig. 11 indicates the estimated M_s in this region. Similarly in Fig. 12, the M_s was determined in cooling path 2J by the MPM. The broken line drawn through cooling path 2G, 2H, and 2I indicates the estimated M_s for 300-M.

In 4340, a limitation of the MPM was also encountered in the determination of the B_s for cooling paths that passed through the tip of the pearlite nose. Fortunately, the B_s could be determined with the MPM in cooling path 1J. Again, the broken line represents the estimated B_s in the region where it was difficult to determine experimentally.

A number of investigators[2,6,9] have determined CCT diagrams for 4340. The M_s determined by other investigators is compared to those obtained in the present study are shown in Table II. Those of the present study are slightly lower. The position of the bainite start time was in good agreement with the magnetic method of Chapman and Jominy[9] and the metallographic method of Blickwede and Hess.[2] The CCT diagram for 4340 published in Metal Progress Databook[16] shown in Fig. 13 compares favorably that of the present study, Fig. 11. The observed spread in M_s values reported by investigators using the several different techniques can be caused by minor variations in heat treatment or composition. Thus, no conclusions can be drawn from the data in Table II as to which technique is best for the measurement of M_s temperatures.

It was found by a previous investigator that 300-M retained a large amount of austenite when transformed isothermally in the bainitic and martensitic ranges.[15] Similarly, in this investigation a large amount of retained austenite was found to exist at room temperature for certain cooling paths. Previously published CCT diagrams have shown that the transformation goes to completion at any cooling velocity. The published CCT diagram by W. W. Cias[17] is shown in Fig. 14 for comparison. It differs considerably in detail with the diagram constructed with the MPM technique (Fig. 12). Although the general shape is similar.

Selected cooling paths were chosen for optical metallography. A series of micrographs of 4340 and 300-M, showing the microstructural variations as the cooling velocity was decreased, is shown in Figs. 15 and 16, respectively. The structure resulting from a gas quench is shown in Fig. 15a. With progressively slower cooling velocities, the series Fig. 15b and c, show an increasing amount of transformation to bainite, indicated by arrows on the photomicrographs. At slower cooling velocities, the cooling paths pass through the pearlite nose. A small amount of proeutectoid ferrite is indicated by the MPM; however, it is difficult to see in the photomicrographs, Fig. 15d and e. The quantitative measurements of the transformation products for each cooling path in Fig. 11 are given in Table III. Hardness measurements (VHN) verified the expected decrease of transformation to martensite as the cooling velocity decreased.

The pearlitic hardenability of 300-M was found to be very high. Cooling paths as slow as 2J still do not show any evidence of the pearlite transformation. The series of micrographs, Fig. 16a-e, show the microstructures of specimens cooled at progressly slower rates. The structure formed in a gas quench is shown in Fig. 16a. As the cooling velocity decreased, a progressive increase in the amount of bainite was evident, indicated in Fig. 16d by arrows. A large amount of retained austenite was measured by the MPM, but it was difficult to verify its presence by the relatively low resolution of optical metallography. The structure shown in Fig. 16e is believed to be a mixture of bainitic ferrite and retained austenite. Table IV shows the quantitative measurements of the transformation products for each cooling path shown in Fig. 12. Again microhardness measurements indicated that smaller amounts of martensite form as the cooling velocity is decreased.

B. Analysis of Data

The quantitative measurements by MPM showed that a large amount of austenite may be retained for 300-M at room temperature. The cooling paths that pass through the tip of the bainite nose show that as the cooling velocity decreases the amount of retained austenite increases with only a slight increase in bainite. This trend is shown in Table III for cooling curves 1B, 1C and 1D. In Table IV, all the cooling curves show this trend. This suggests that the initial transformation to bainite stabilizes some of the untransformed

austenite.[20] Troiano[21] found that retained austenite was present at room temperature by water quenching specimens of SAE 5140 that were partially transformed to bainite. Upper bainite was found to be more effective than lower bainite in retaining austenite at room temperature.[21,22]

In 4340, an analysis of the stabilizing effect of bainite is complicated by the transformation to proeutectoid ferrite at the tip of the pearlite nose. Along cooling paths 1F-1J, small amounts of proeutectoid ferrite form and this appears to decrease the amount of retained austenite (as compared to cooling path 1E). However, the proeutectoid ferrite also has a stabilization effect on the austenite. The quantitative measurements show that the amount of retained austenite increases with only a slight increase in proeutectoid ferrite. This may be seen in Table III for cooling paths 1F-1I.

As can be seen from Table III, for cooling path 1E, 22% of the austenite transformed to bainite whereas for paths 1F and 1G, the microstructure have 16% and 19%, respectively. These results suggest that the critical segment of the cooling path is between the B_s and M_s temperatures. For path 1E, the total time spent in this temperature range was 195 seconds; for paths 1F and 1G, these values were 215 and 250 seconds, respectively. The length of time spent in the bainitic transformation temperature range apparently determines how much austenite will be retained. This conclusion, if valid, is pivotal to the selection of critical cooling paths which will result in the maximum amount of retained austenite. This microstructure appears to

offer great toughness of high ultimate strength levels, i.e., greater than 200,000 psi.[19]

IV. CONCLUSIONS

1. A magnetic permeability technique developed for the study of the transformation kinetics of low alloy during programmed cooling proved to be rapid, accurate and precise.
2. Large amounts of retained austenite (up to 18%) were present at room temperature in 4340 when the cooling path passed through the temperature range corresponding to the tip of the bainite nose.
3. In 300-M, the amount of retained austenite was found to be as high as 45% for certain critical time-temperature paths.
4. In the time-dependent transformations, the amount of retained austenite depended on the length of time the specimen was in the bainite temperature range.

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Table I. Chemical Analysis (given in wt%)

	C	Mn	Si	Cr	Ni	Mo	Cu	S	P	V
AISI 4340	0.395	0.70	0.28	0.76	1.70	0.23	0.22	-	-	-
AMS 6416 (300-M)	0.41	0.79	1.59	0.75	1.85	0.43	0.04	0.002	0.008	0.08

Table II. Comparison of CCT Diagrams

	Method used to construct CCT diagram			
	Present MPM	Dilatometry[6]	Magnetic Permeability[9]	Metallography[2,16]
M_s	290°C	293°C	300°C	293°C
Position of Bainite nose on the time scale	30 sec	90 sec	30 sec	27 sec

Table III. Quantitative Measurements for 4340 (volume percent).

Cooling Path	Estimated cooling velocity at 450°C, °C/sec	Ferrite Formed in the Pearlite Range, %	Bainite, %	Martensite, %	Retained Austenite, %	VHN
1A	72	-	-	100	-	616
1B	9.1	-	0.2	91	8.8	-
1C	6.7	-	0.5	90	9.5	-
1D	5.1	-	1	85	14	567
1E	2.2	-	22	60	18	466
1F	1.6	0.1	16	71	12.9	-
1G	1.2	0.2	19	69	11.8	-
1H	0.74	0.2	30	56	13.8	442
1I	0.4	0.5	60	24	15.5	-
1J	0.1	1	89	5	5	301

Table IV. Quantitative Measurements for 300-M (volume percent).

Cooling Path	Estimated cooling velocity at 450°C, °C/sec	Ferrite Formed in the Pearlite Range, %	Bainite, %	Martensite, %	Retained Austenite, %	VHN
2A	72	-	-	100	-	654
2B	7.7	-	-	89	11	-
2C	3.1	-	0.1	78	21.9	622
2D	2.8	-	0.3	76	23.7	-
2E	1.9	-	0.5	79	20.5	-
2F	0.8	-	0.4	75	24.6	618
2G	0.4	-	9	65	26	616
2H	0.2	-	33	36	31	-
2I	0.1	-	49	6	45	425
2J	0.09	-	56	1	43	-

FIGURE CAPTIONS

Fig. 1. Photograph of the continuous cooling system.

Fig. 2. Block diagram of the MPM electronic system.

Fig. 3. Block diagram of the electronics for programmed cooling along with a skematic of the continuous cooling apparatus.

Fig. 4. Photograph of a shorten specimen. The thermocouple junction was made about 6 inches down from the formed hook.

Fig. 5. Example of temperature-time traces from tests of thermocouple circuits.

Fig. 6. Illustrates the attachment features on the right end cap.

Fig. 7. Illustrates the attachment features on the left end cap.

Fig. 8. Illustrates the position of the specimen during an experimental run.

Fig. 9. Temperature-structure calibration curves for 4340 and 300-M.

Fig. 10. Volume fraction calibation curve.

Fig. 11. Continuous cooling transformation diagram for 4340.

Fig. 12. Continuous cooling transformation diagram for 300-M.

Fig. 13. CCT diagram for 4340 published in Metal Progress Databook.

Fig. 14. CCT diagram for 300-M published in AFS Trans. by W. W. Cias.

Fig. 15. Series of photomicrographs for 4340 illustrating the microstructural variation with cooling velocity.

a. Cooling path 1A. Mainly lath martensite with a small amount of plate martensite indicated by arrows. (VHN is 616)

b. Cooling path 1D. MPM detected ~1% bainite. Arrows indicate regions of bainite (VHN is 567).

c. Cooling path 1E. MPM detected ~22% bainite. Arrows indicate regions of bainite. (VHN is 466)

d. Cooling path 1H. MPM detected ~30% bainite (VHN is 442).

e. Cooling path 1J. MPM detected ~89% bainite. (VHN is 301)

Fig. 16. Series of photomicrographs for 300-M illustrating the microstructural variation with cooling velocity.

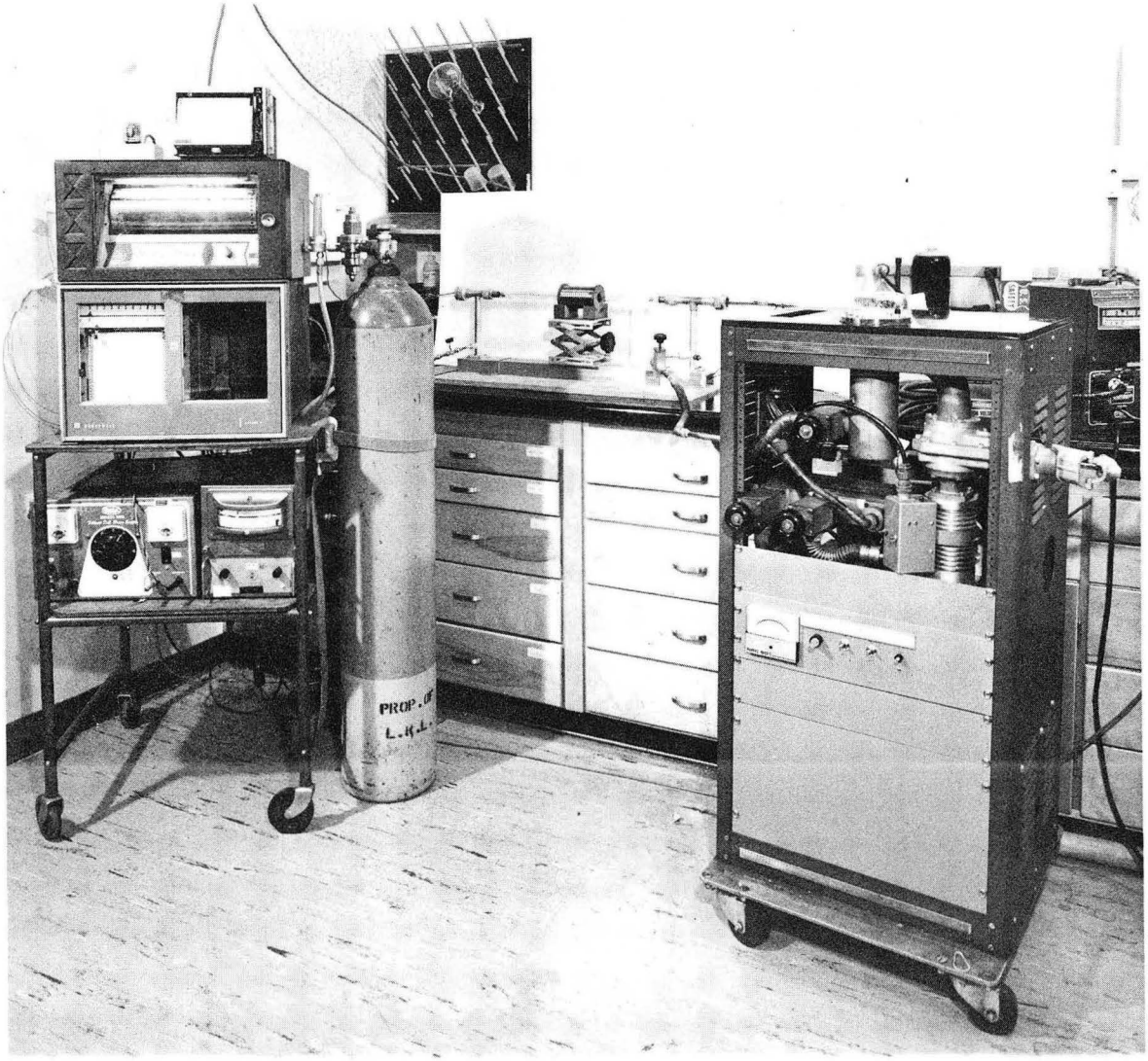
a. Cooling path 2A. Mainly lath martensite with a small amount of plate martensite indicated by arrows. (VHN is 654)

b. Cooling path 2C. MPM detected ~ 0.1% bainite and ~21.9 austenite. It is difficult to resolve this structure optically. (VHN is 622)

c. Cooling path 2F. MPM detected ~ 0.4% bainite and ~24.6% austenite. Again it is difficult to resolve optically (VHN is 618).

d. Cooling path 2G. MPM detected ~9 bainite. Arrows indicate regions of bainite. (VHN is 616)

e. Cooling path 2I. MPM detected ~49% bainite and ~45% austenite. Structure believed to be a mixture of bainite ferrite and austenite. (VHN is 425)



XBB 736-3674

Fig. 1.

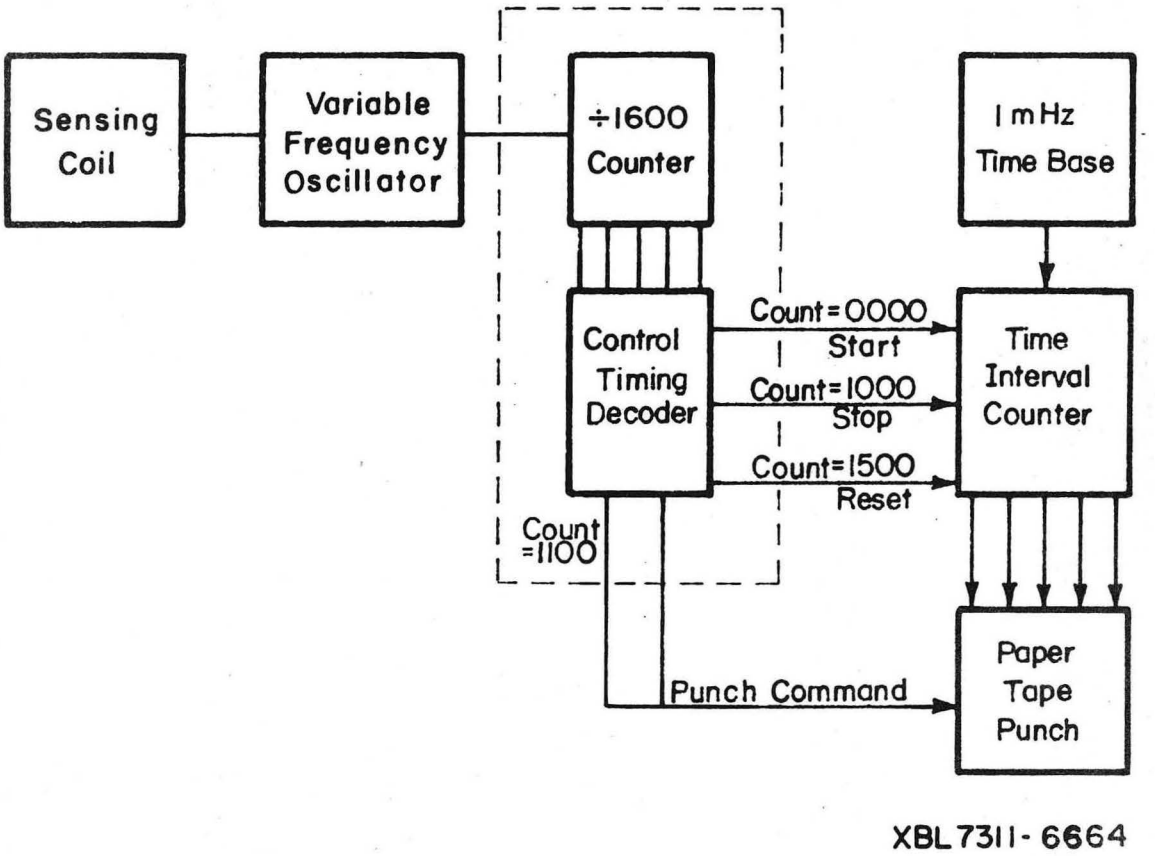
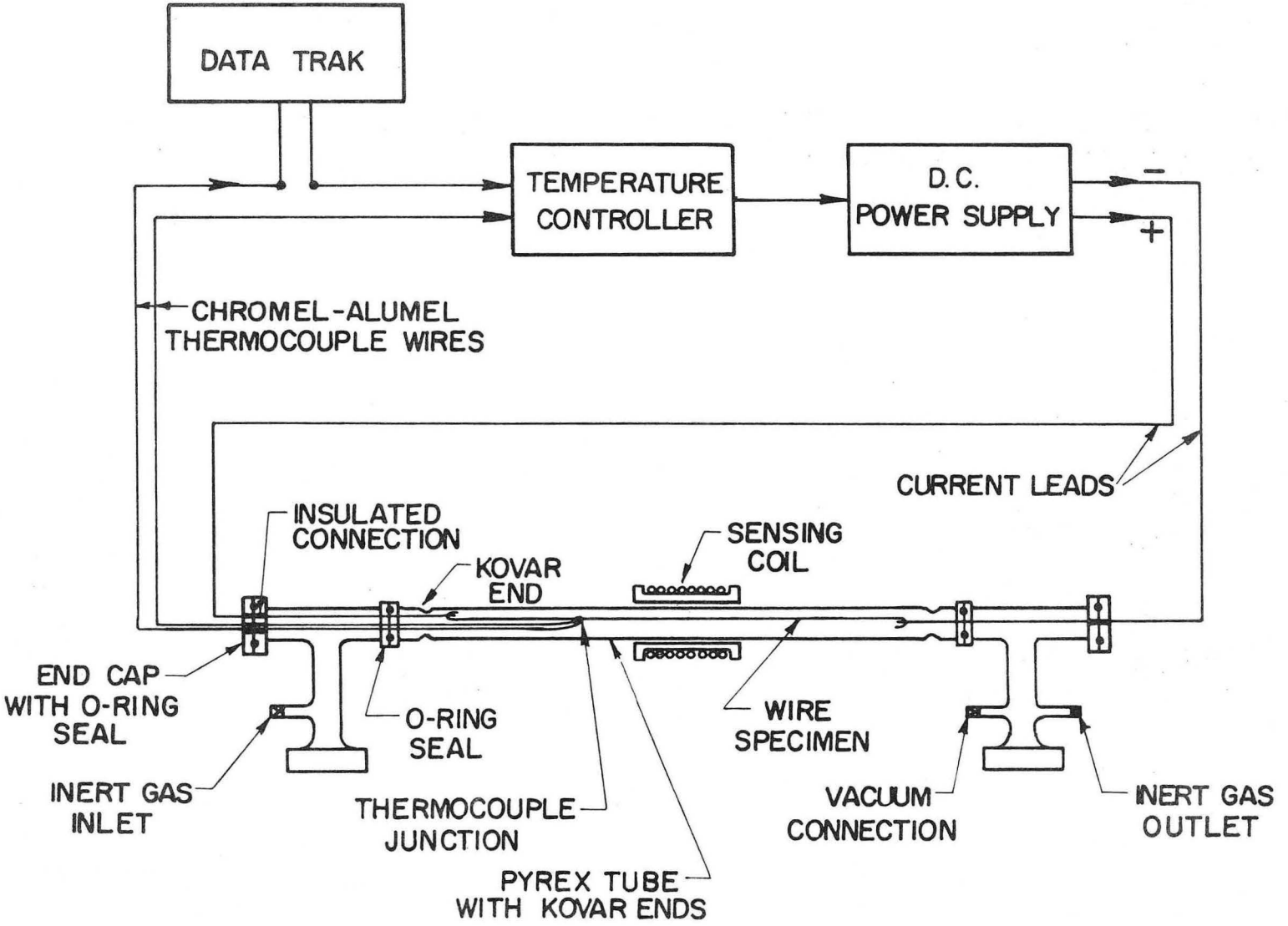
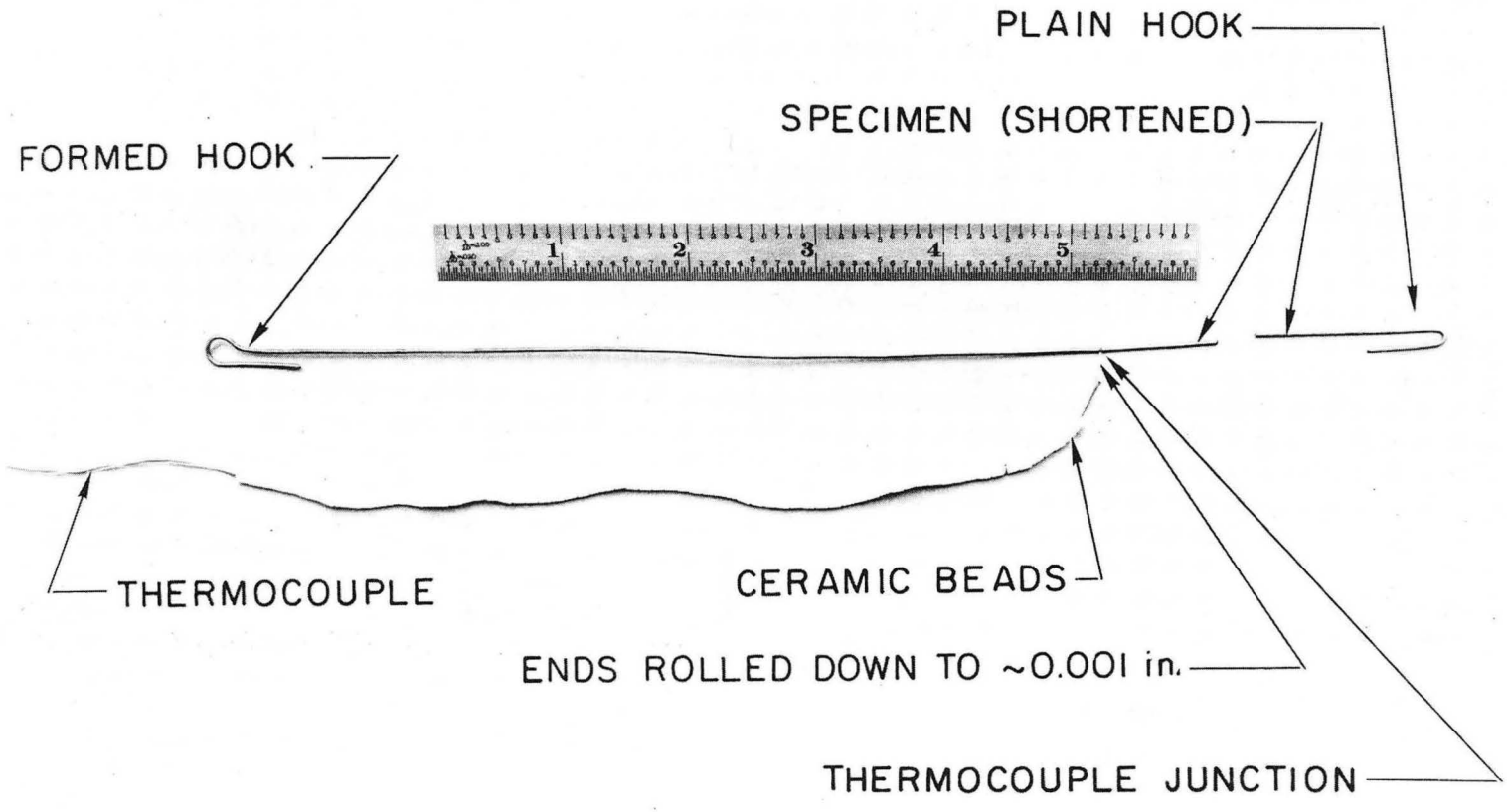

Sensing Coil
Variable Frequency Oscillator
÷1600 Counter
1 mHz Time Base
Control Timing Decoder
Count=0000 Start
Count=1000 Stop
Count=1500 Reset
Time Interval Counter
Count =1100
Punch Command
Paper Tape Punch
XBL7311-6664

Fig. 2.



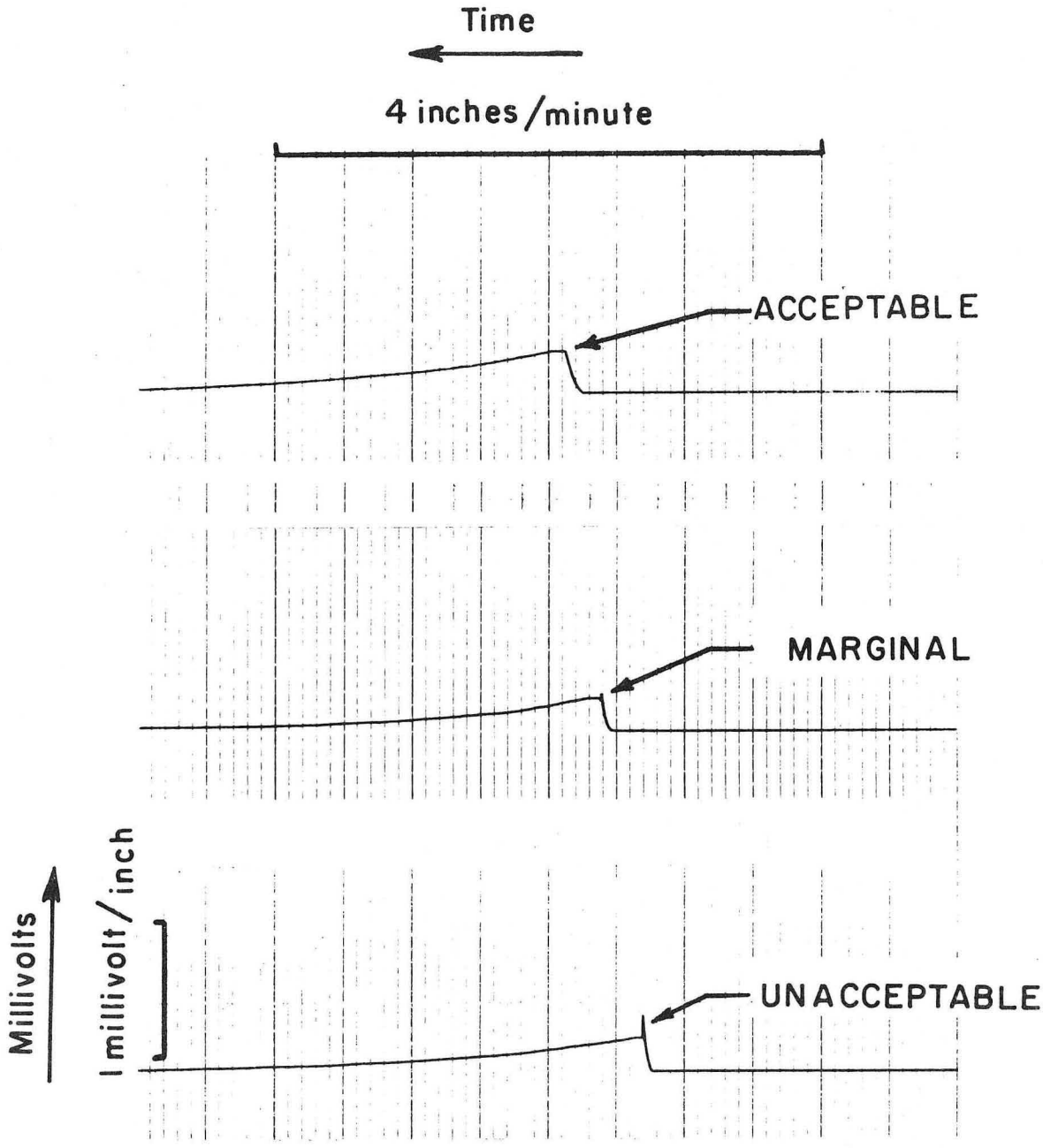
XBL742-5593

Fig. 3.



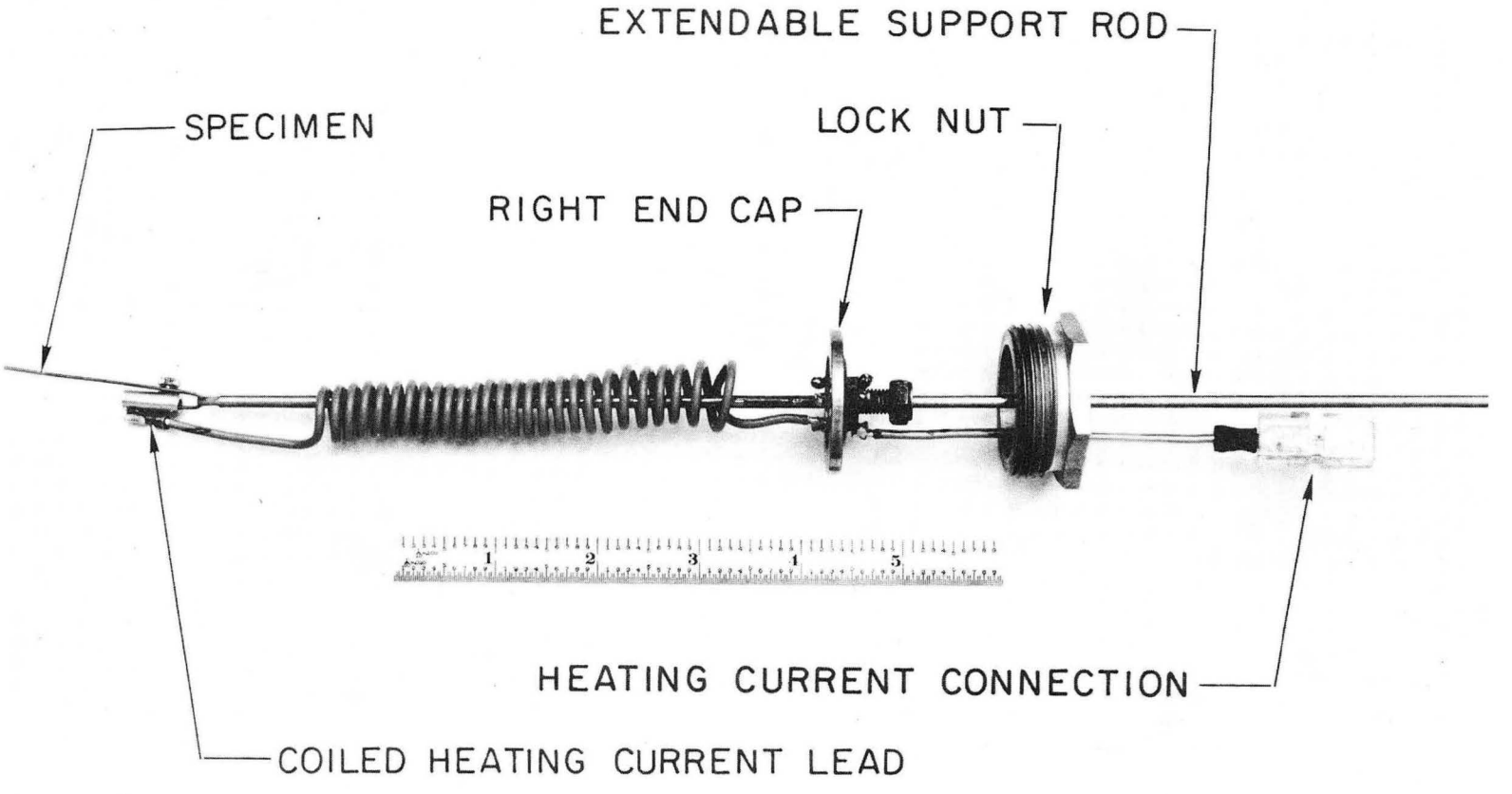
XBB 747-4152A

Fig. 4.



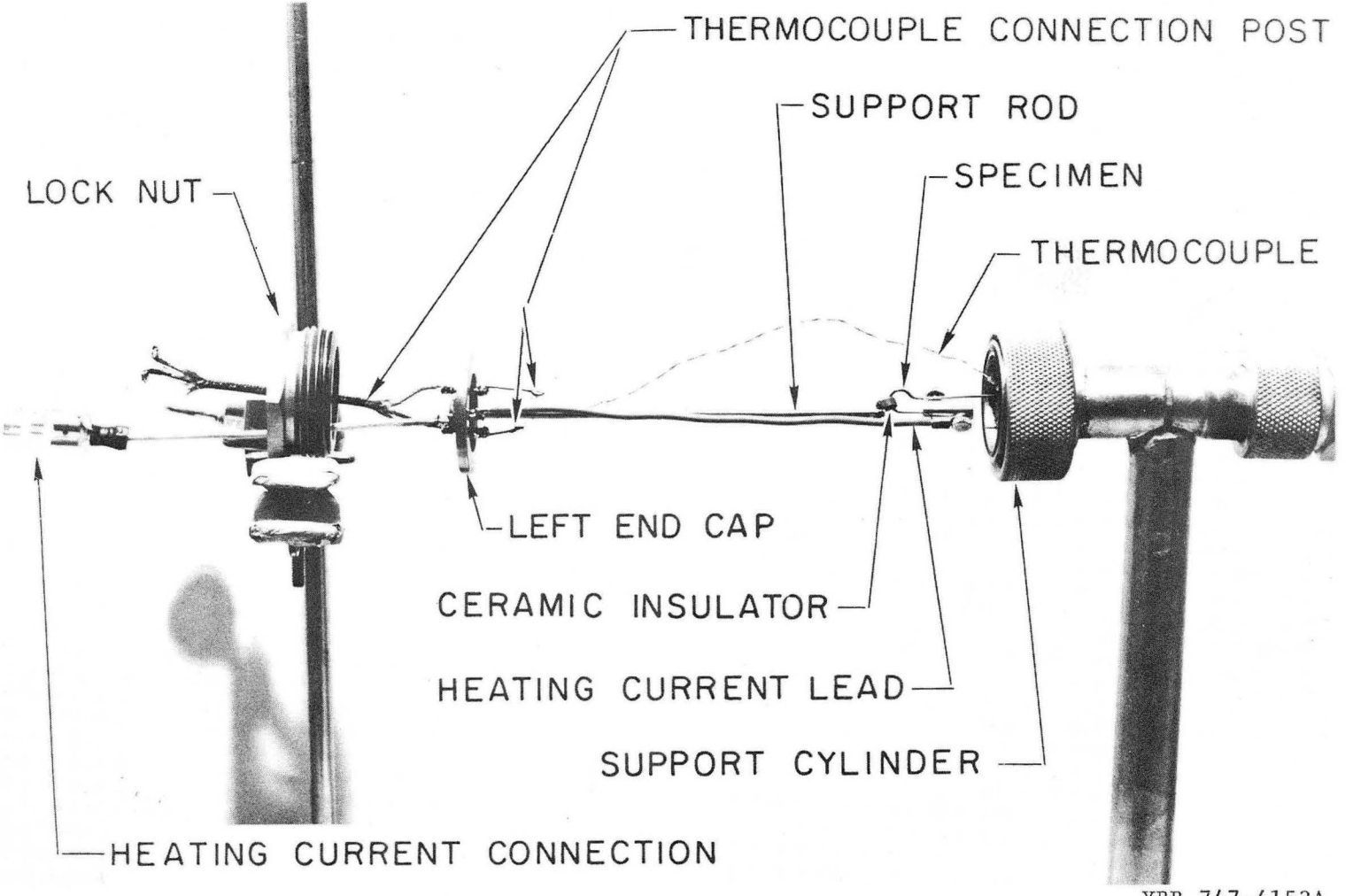
XBL 747-6697

Fig. 5.



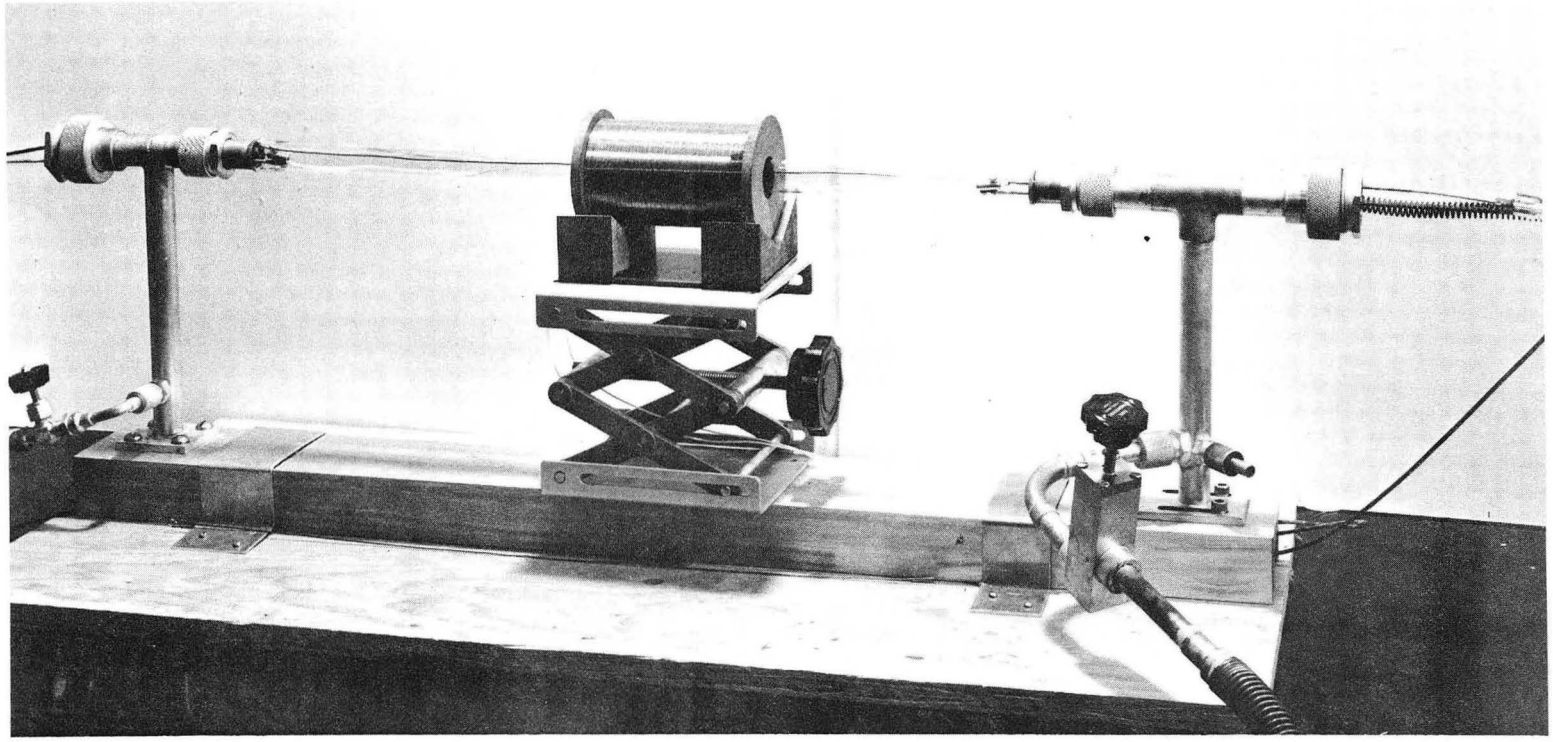
XBB 747-4151A

Fig. 6.



XBB 747-4153A

Fig. 7.



XBB 736-3673

Fig. 8.

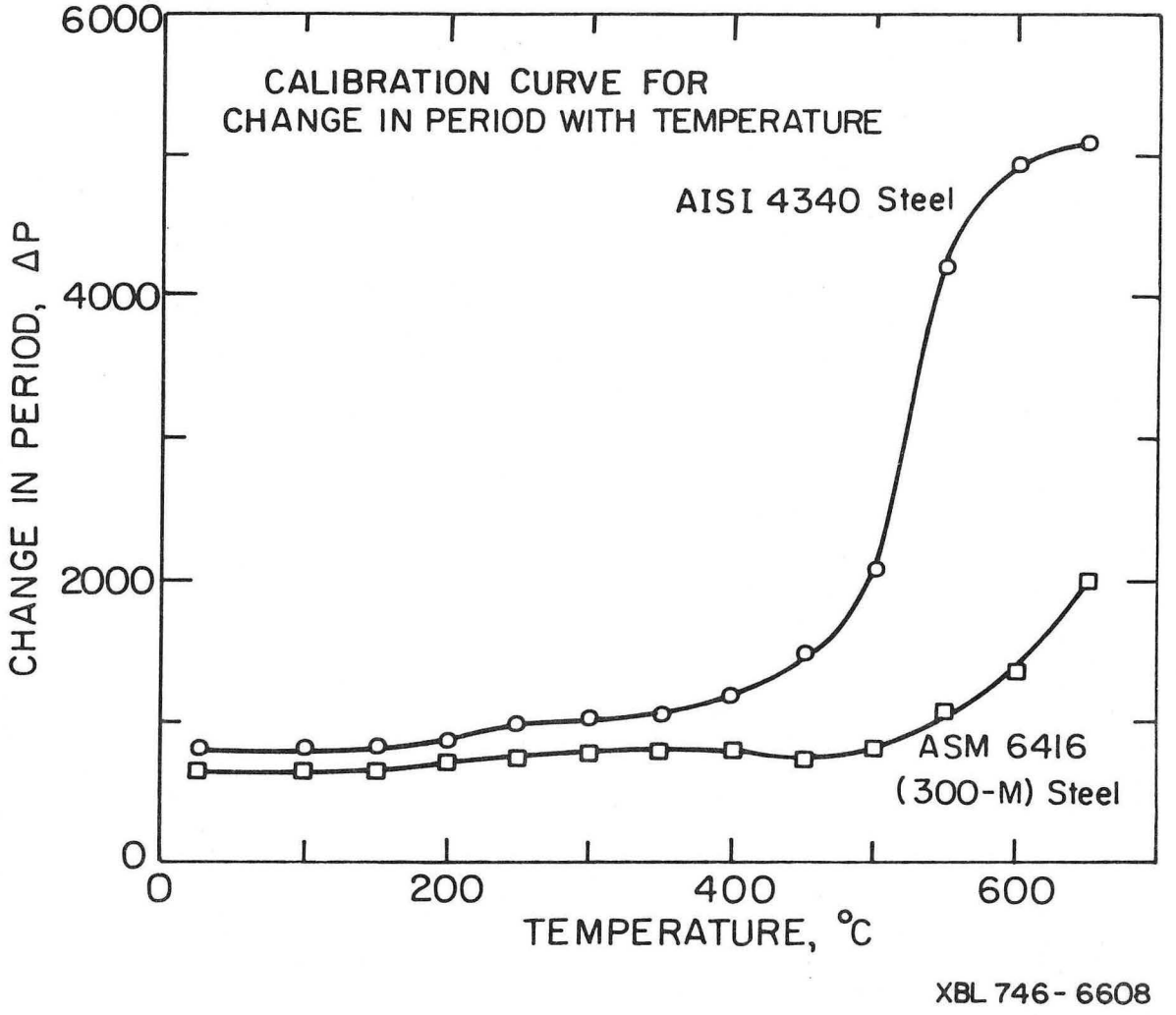

CALIBRATION CURVE FOR
CHANGE IN PERIOD WITH TEMPERATURE
AISI 4340 Steel
ASM 6416
(300-M) Steel
CHANGE IN PERIOD, ΔP
TEMPERATURE, °C
0
2000
4000
6000
0
200
400
600
XBL 746-6608

Fig. 9.

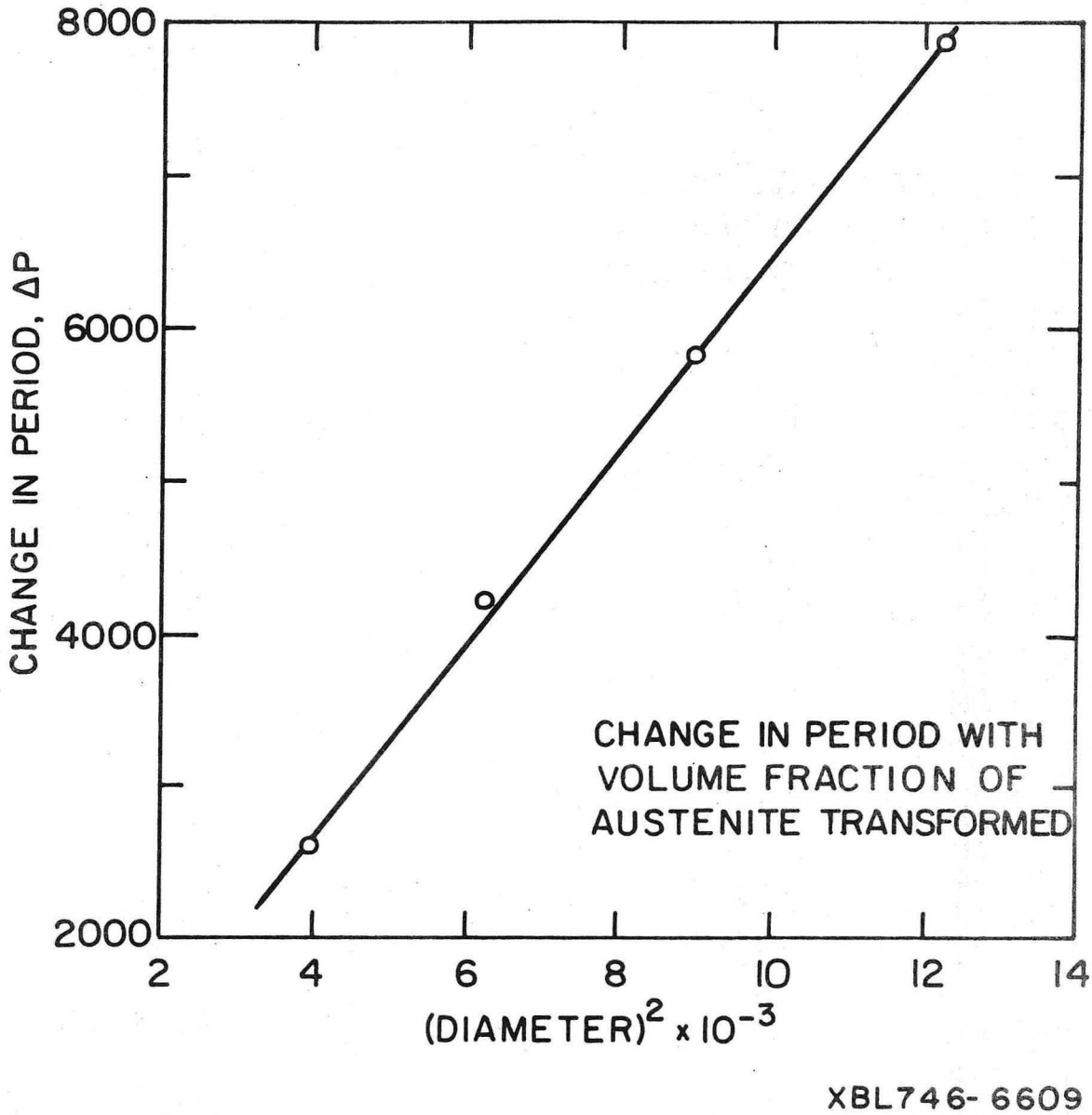

8000
6000
4000
2000
CHANGE IN PERIOD, ΔP
2
4
6
8
10
12
14
(DIAMETER)^2 x 10^{-3}
CHANGE IN PERIOD WITH
VOLUME FRACTION OF
AUSTENITE TRANSFORMED
XBL746-6609

Fig. 10.

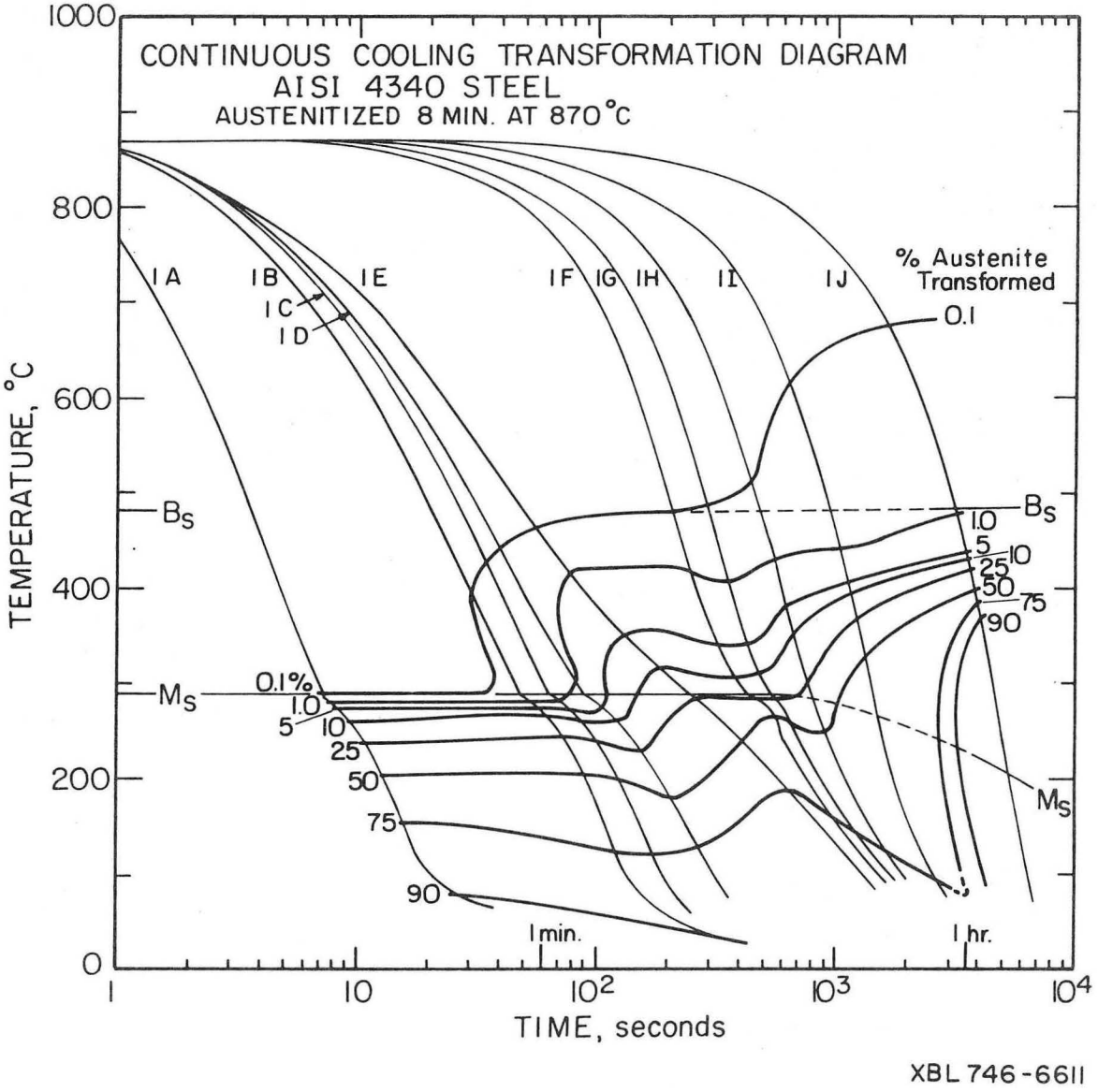

CONTINUOUS COOLING TRANSFORMATION DIAGRAM
AISI 4340 STEEL
AUSTENITIZED 8 MIN. AT 870°C
TEMPERATURE, °C
TIME, seconds
1000
800
600
400
200
0
1
10
10²
10³
10⁴
1 min.
1 hr.
1A
1B
1C
1D
1E
1F
1G
1H
1I
1J
% Austenite Transformed
0.1
1.0
5
10
25
50
75
90
0.1%
Bs
Ms
XBL 746-6611

Fig. 11.

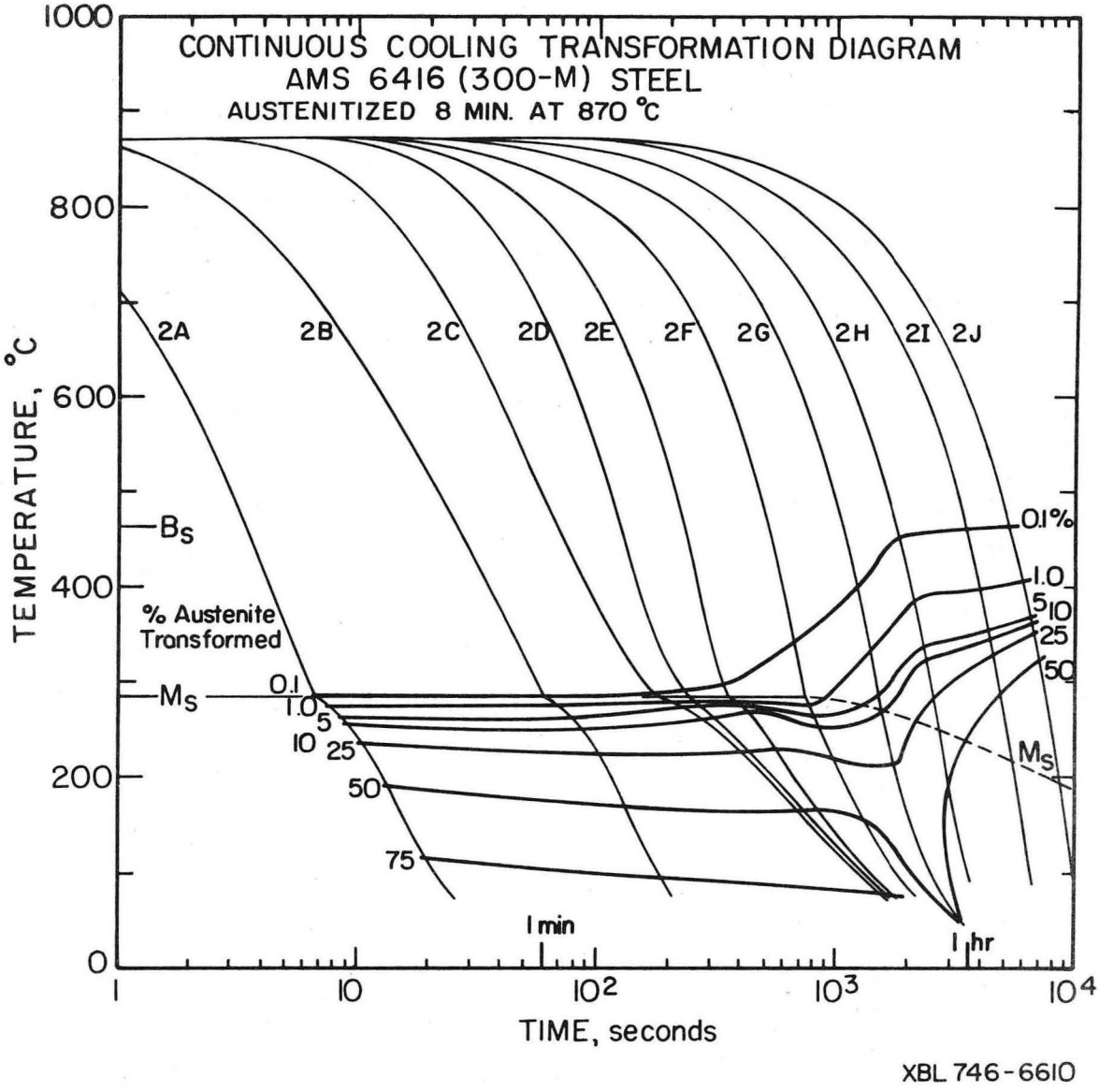
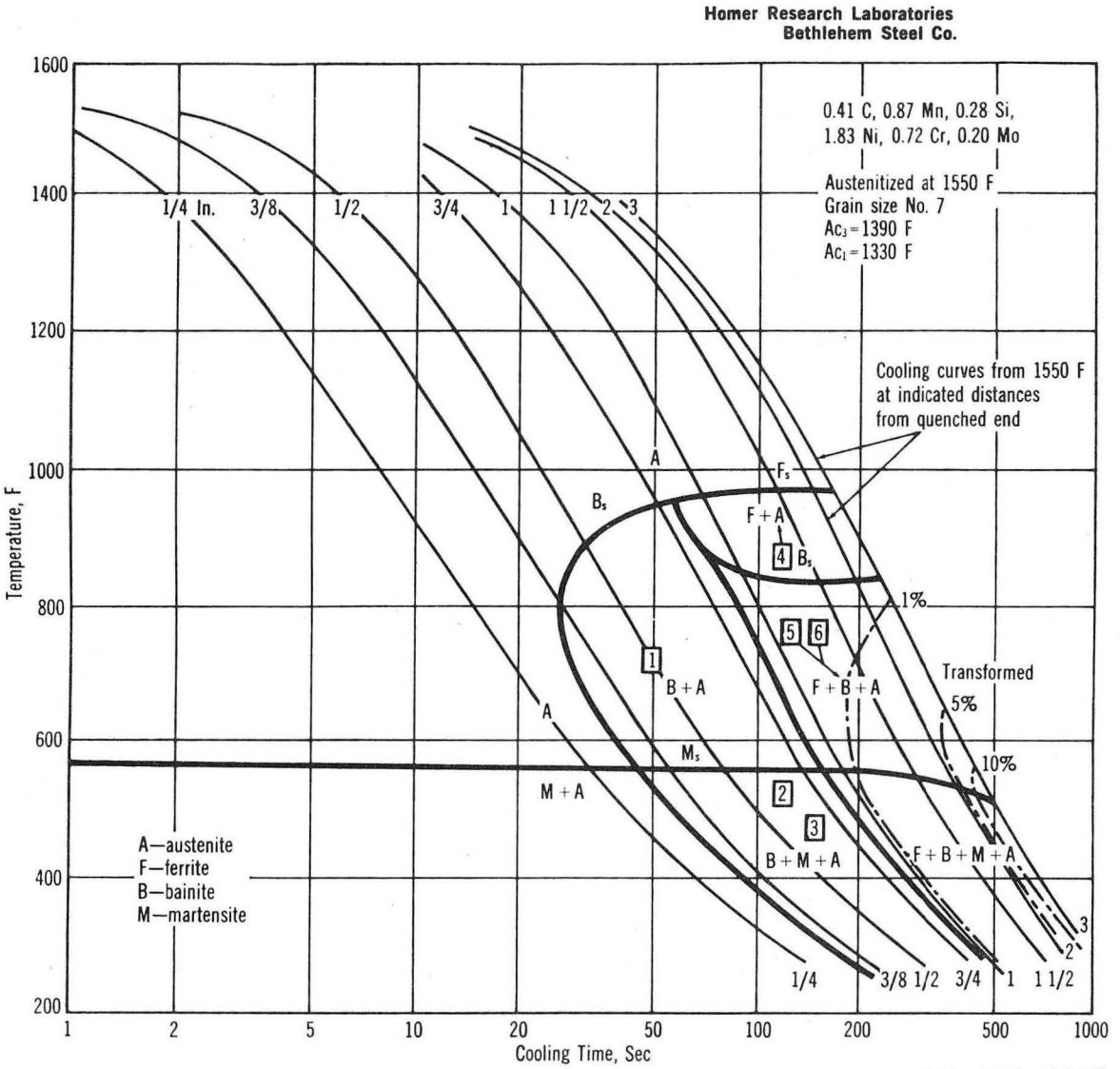

CONTINUOUS COOLING TRANSFORMATION DIAGRAM
AMS 6416 (300-M) STEEL
AUSTENITIZED 8 MIN. AT 870 °C
TEMPERATURE, °C
TIME, seconds
1000
800
600
400
200
0
1
10
10²
10³
10⁴
2A
2B
2C
2D
2E
2F
2G
2H
2I
2J
Bs
Ms
% Austenite Transformed
0.1
1.0
5
10
25
50
75
0.1%
1.0
5
10
25
50
Ms
1 min
1 hr
XBL 746-6610

Fig. 12.

for AISI 4340



XBL 746-6637

Fig. 13.

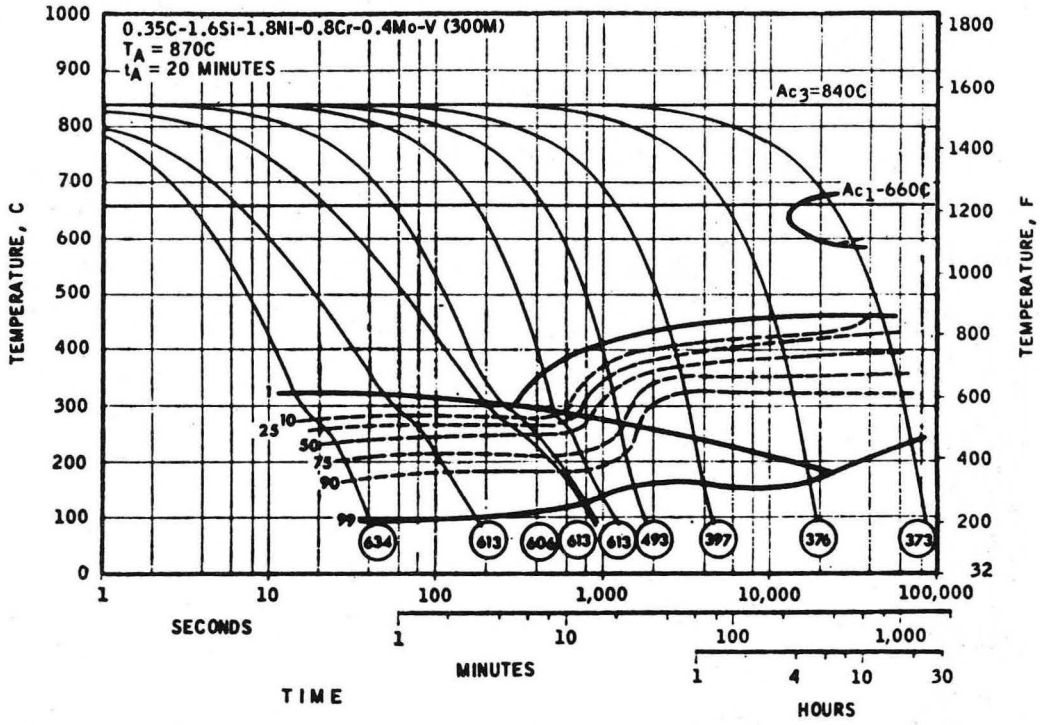


Fig. 5. Continuous cooling transformation diagram for the 0.33C-1.6Si-1.8Ni-0.8Cr-0.4Mo-V (300M) cast steel containing 0.33% C, 1.62% Si, 1.80% Ni, 0.81% Cr, 0.40% Mo and 0.067% V, austenitized at 870C (1600F) for 20 min.

XBL 746-6638

Fig. 14.

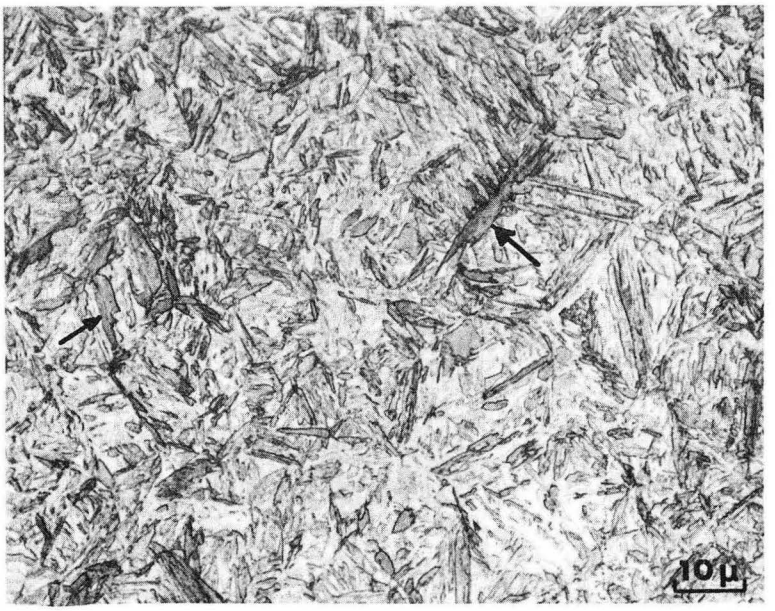
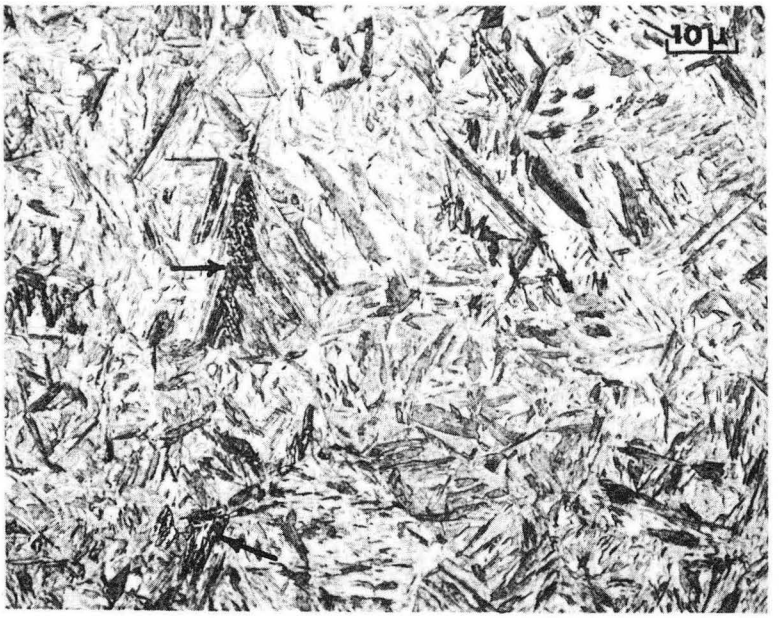


Fig. 15(a)



XBB 746-4161

Fig. 15(b).

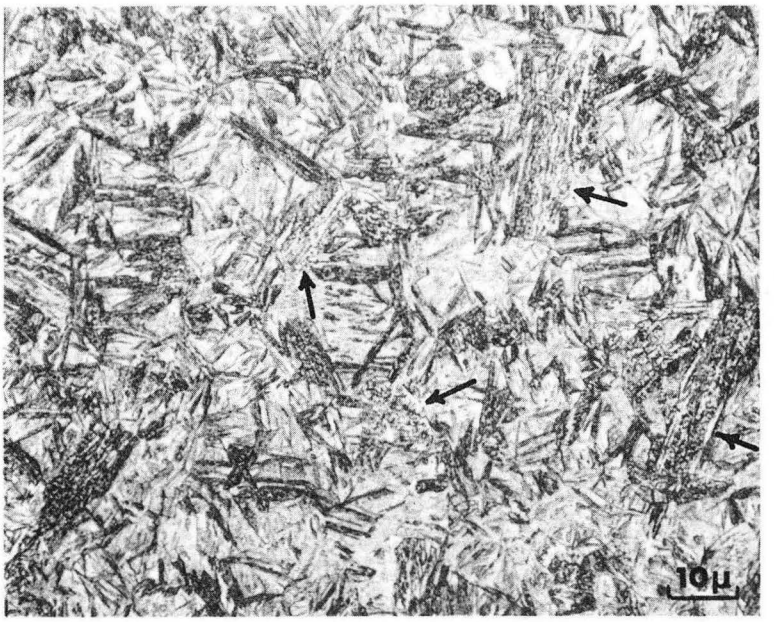
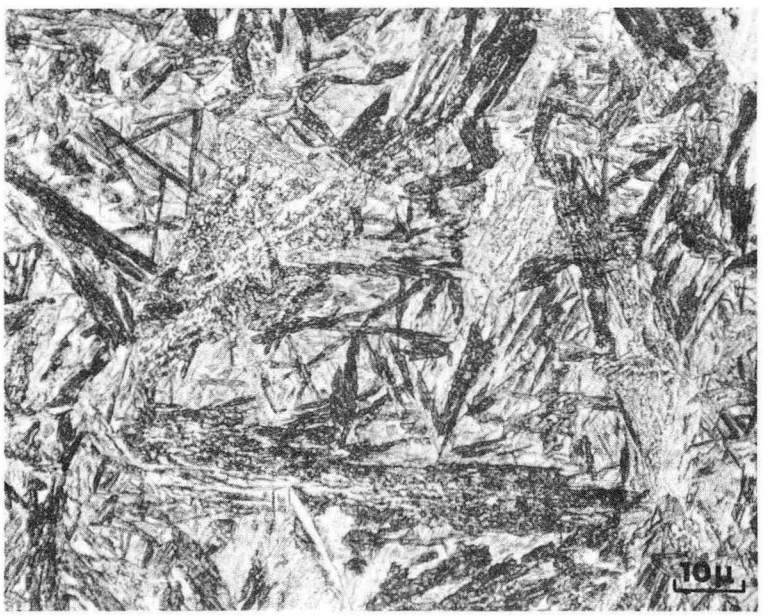


Fig. 15(c)



XBB 746-4160

Fig. 15(d)

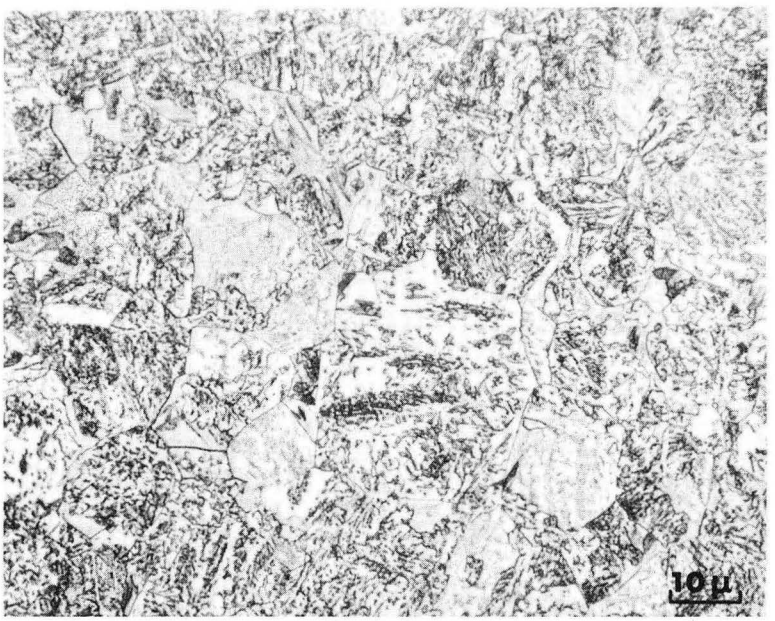
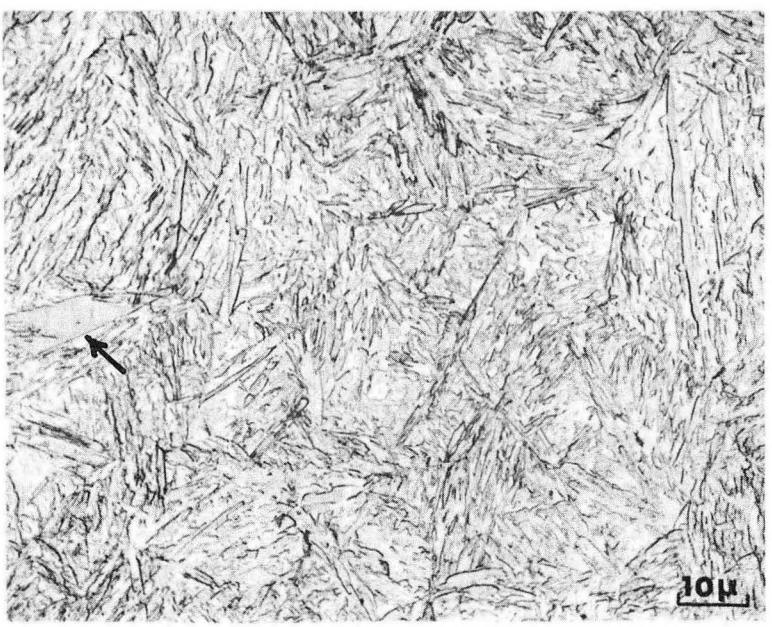


Fig. 15(e)



XBB 746-4159

Fig. 16(a)

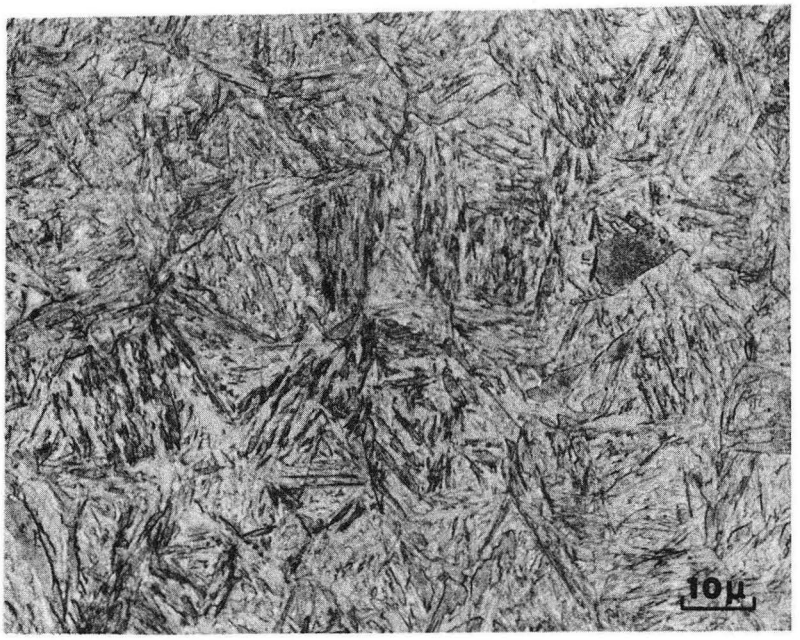
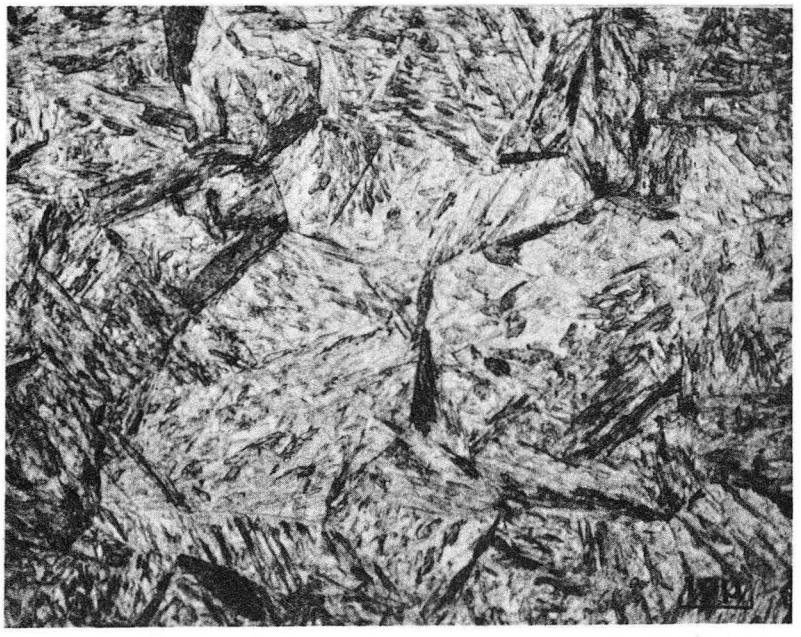


Fig. 16(b)



XBB 746-4158

Fig. 16(c)

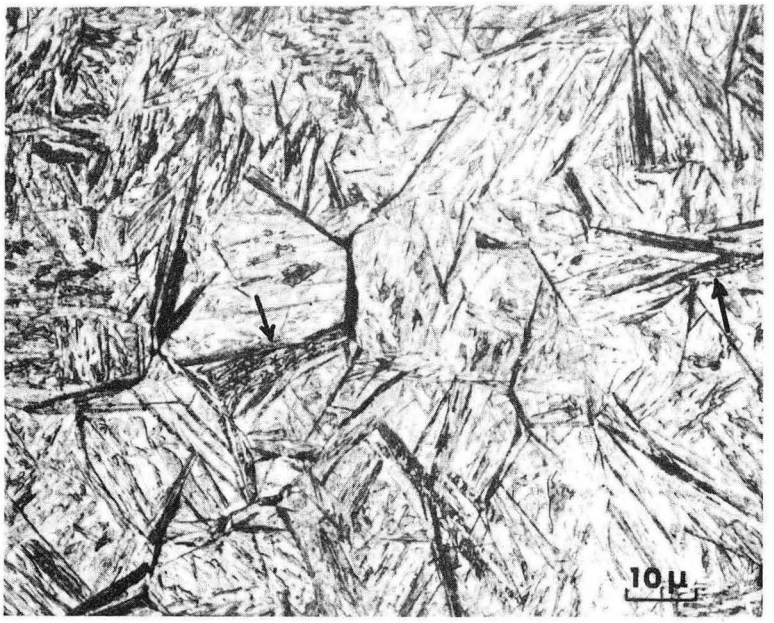
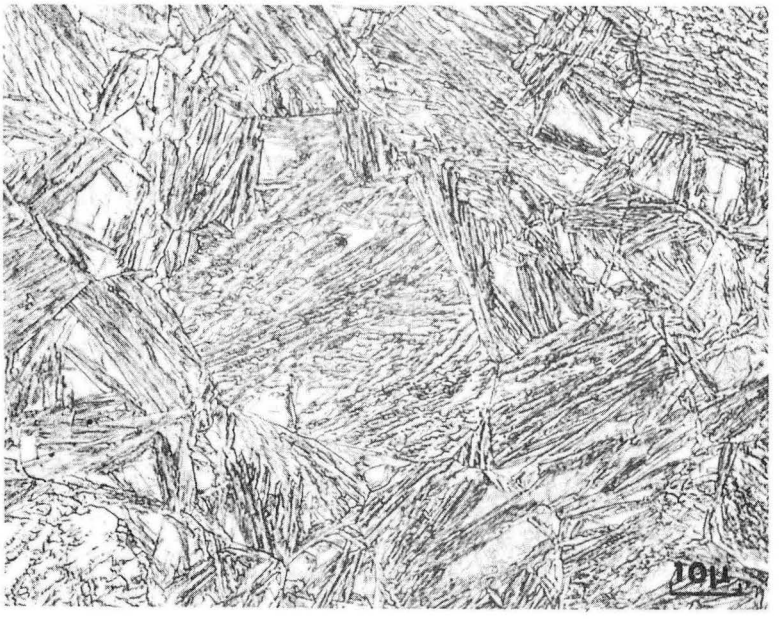


Fig. 16(d)



XBB 746-4157

Fig. 16(e)

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