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Mechanical and Physical Properties of TZM Molybdenum Alloy Sheet and of Tungsten Sheet

November 15, 1963

Prepared under Bureau of Naval Weapons
Contract N600(19)59530

Fourth Quarterly Progress Report

SOUTHERN RESEARCH INSTITUTE
2000 9th Avenue S. Birmingham 5, Alabama

PUBLICITY

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Fourth Quarterly Progress Report
(August 1 through October 31, 1963)

Southern Research Institute
Birmingham, Alabama
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Fourth Quarterly Progress Report on

Mechanical and Physical Properties of TZM Molybdenum Alloy Sheet and of Tungsten Sheet

INTRODUCTION

This is the fourth progress report on a program to determine preliminary design data for tungsten and TZM molybdenum sheet produced in Phase I of the Refractory Metal Sheet Program. Fansteel Metallurgical Corporation produced the tungsten sheet on Bureau of Naval Weapons (BuWeps) Contract No. NOw-60-0621-c, and Universal-Cyclops Steel Corporation is producing the TZM alloy sheet on Navy Contract No. NOas59-6142c. The work described in this progress report was performed during August, September and October, 1963.

The experimental work that has been performed on the program so far has been limited to the tungsten sheet because the TZM sheet, which was produced after the tungsten sheet, has not been received. The tungsten sheet material was received by Southern Research Institute (SRI) about mid-June, 1963.

In the previous progress reports we reviewed the scope and purpose of the program, described the experimental procedures and equipment that would be used, and in the last progress report, for May, June, and July, 1963, we presented preliminary information on the determination of the recrystallization temperature of the tungsten sheet.

During the period which this report covers—August, September, and October, 1963—we have continued with the preparation of specimens from the tungsten sheet materials, completed the determination of the recrystallization temperatures, and conducted the compression and bend-property evaluations on the sheet in the optimum condition. Additional compression, bend, and a few tensile specimens have been sent to an outside contractor to be recrystallized for subsequent evaluations. The original plan to evaluate both the TZM and tungsten sheet in the coated condition has been revised to eliminate the evaluation of coated tungsten sheet, to increase the evaluation of the coated TZM sheet, and to coordinate the work on the coated TZM sheet with an Air Force program on coatings at the University of Dayton Research Institute.

MATERIALS AND SPECIMENS

Although we have not received the TZM sheet, we have been advised by BuWeps that the required quantities of 0.020, 0.040, and 0.060 in. thick sheet scheduled for evaluation on the program would be supplied during November.

The description and processing of the tungsten sheets that were supplied for the program was reviewed in our third progress report. Figure 1 shows the microstructure in the longitudinal and transverse orientations of the three 0.060 in. thick tungsten sheets supplied for the program. The microstructure in the longitudinal and transverse orientations of the 0.100 in. thick sheet is shown near the top of Figure 6. As Figure 1 shows, the warm-worked microstructure of sheet 6 seems to be coarser than that of sheets 15 and 17, which probably results from a difference in the grain size of the sheet bars or of the plate after one of the intermediate anneals. Although the full consequence of this difference in the microstructure of sheet 6 from the other sheets can not be fully evaluated until additional data are obtained, the bend-transition data and the recrystallized microstructure, to be discussed in later sections of the report, indicate a probable difference in this sheet from sheets 15 and 17. The final report on BuWeps Contract No. NOw-60-0621-c, on which the tungsten sheet was produced, was reviewed in an attempt to determine the reason for the apparent difference in the microstructure of sheet 6, but the report does not indicate any significant difference in the processing of sheet 6 from the other sheets.

All of the specimen blanks for the scheduled evaluations of the tungsten sheets have been cut from the locations shown for each sheet in our previous progress report. A repetitive sampling procedure was used to distribute, insofar as practical, the specimens from different sheets among the various evaluation conditions to determine differences in the properties of the different sheets.

The preparation of specimens from the tungsten sheet is in general proceeding satisfactorily. However, we were unable to machine the loading holes in tensile specimens to the required tolerances with the electro-chemical milling apparatus discussed in our previous progress report. By use of carbide drills and a special fixture, however, we have successfully drilled loading holes in all of the tensile specimens for evaluations above the transition temperature. In preliminary tensile tests at room temperature, the specimens failed at the loading holes rather than in the gage section, but at 1200° F the specimen did not fail at the holes. In future evaluations pin loaded specimens will be utilized when possible, and shoulder loaded specimens, as discussed in our proposal, will be used for other evaluations.

Based on results from the determination of the recrystallization temperature of the two tungsten sheet gages, 0.060 and 0.100 in., 2550° F for 60 min at temperature was selected as the condition for recrystallization of the tungsten specimens for the different evaluations. Specimens for determination of the compression and bend evaluations and part of the tensile evaluations have been sent to the "Ipsenlab" for recrystallization.

EXPERIMENTAL PROCEDURES AND RESULTS

A. Recrystallization

The procedures and apparatus that were used for determination of the recrystallization parameters were discussed in detail in our previous progress report. Briefly, however, strip specimens, 3/8 in. wide x 7 in. long, were resistance heated in a vacuum of 1.5×10^{-4} torr to temperatures between 1800 and 3200° F and held at temperature for 5 and 60 min. The Rc surface hardness, the DPH at the mid-thickness, and metallographic estimates of the percentage of recrystallized structure were determined to establish the recrystallization characteristics of the 0.060 and 0.100 in. tungsten sheet gages. Two observers independently estimated the percentage of recrystallized structure, and the results of these independent observations were averaged to determine the values given in the report.

For the 0.060 in thick sheet, determination of the recrystallization characteristics is based mainly on results from sheet number 15; however, the recrystallization behavior of sheet numbers 6 and 17 was checked against that of sheet number 15 at five different time-temperature combinations.

Results of the hardness measurements and estimates of recrystallized structure for the 0.060 and 0.100 in. thick tungsten sheets are given in Tables I and II and are plotted as functions of temperature in Figures 2 through 6. The plots of data for the three different 0.060 in. thick sheets, Figures 2, 3, and 5, show that the decrease in hardness and increase in the percentage of recrystallized structure for the three sheets are comparable for the same conditions of temperature and time. The recrystallized structure of sheet 6; however, is different from that of sheets 15 and 17 as shown in Figure 7. The recrystallized structures of sheets 15 and 17 are uniform and have a grain size of about ASTM No. 8, while the structure of sheet 6 is irregular and the grain size ranges from ASTM No. 6 to 2 with some subgrains of about ASTM No. 6 visible within the large grains. It was noted earlier that the structure of sheet 6 in the as-received condition was coarser than that of sheets 15 and 17 and appeared to have had a larger grain size before working than the other sheets.

The recrystallization characteristics of the 0.100 in. thick sheet; as shown in Figures 3, 4, and 6, are approximately the same as for the 0.060 in. thick sheet. Materials Advisory Board Specification MAB-192-M defines the recrystallization temperature as the minimum temperature at which in one hour the structure will be 50 percent recrystallized and the decrease in hardness is 2/3 of the total decrease from the initial condition to the fully recrystallized condition. On this basis, the recrystallization temperature of both the 0.060 and 0.100 in. thick tungsten sheet is 2400° F.

B. Compression Evaluations

Evaluation has been completed of the room-temperature compression properties in both the longitudinal and transverse orientations of the 0.060 in. thick tungsten sheet in the optimum condition.

Sketches of the fixture and the specimen configuration used in the compression determinations are shown in Figures 8 and 9 respectively. Buckling of the compression sheet specimens was prevented by support blocks, shown in Figure 8, which were fastened together by screws and adjustable strap-type clamps. The blocks were polished and lubricated with a heavy lubricant to minimize friction. In general the procedure and apparatus used for these evaluations meet the requirements of ASTM Specifications E9-52T (1)[1] and E209-63T (2).

[1] Numbers in parentheses refer to the bibliography.

Strain was measured at the gage-point lugs by means of a strain-gage extensometer, and load was measured by the weighing system of the Baldwin Universal Testing Machine. A stress-strain curve was recorded with an autographic recorder.

The compression apparatus was qualified in accordance with the recommendations of ASTM Specification E209-63T and the "Uniform Testing Procedures for Sheet Materials, Part 3: Compression Test" (3) prepared by Sub-Panel II (on Uniform Procedures for Structural Design-Data Collection) of the Panel on Titanium Sheet Rolling Program. Briefly, the qualification procedure consists of the determination of the compressive modulus of elasticity of specimens at various temperatures, in this case at room temperature, with the apparatus and comparison of these data with generally accepted values of tensile modulus. If the compression modulus is within ± 5 percent of the tensile modulus, the compression equipment is considered satisfactory. In our particular qualification, 6061-T6 aluminum was evaluated at room temperature and a compression modulus of 9.7 x 10^6 psi was obtained. This value is within ± 5 percent of the generally accepted tensile modulus of 9.5 x 10^6 psi for this material.

Results of the compression evaluations, which are given in Table III, indicate that the 0.2% offset yield strength in compression is lower for the longitudinal orientation than for the transverse orientation. This difference in the yield strengths may be due to the stress reversal between rolling and compression testing (the Bauschinger effect), which would be more pronounced for the longitudinal orientation and would cause the longitudinal yield strength to be lower than the transverse yield strength. The data shown in Table III also indicate that the yield strength of sheet 15 is slightly higher than that of sheet 17. Specimens of sheet 6 in the optimum condition were not evaluated, but in view of differences in the microstructure of sheet 6 from the other sheets, we plan to evaluate compression specimens from sheet 6 in the optimum condition when the fixture is set up later for evaluation of the compression properties of the fully recrystallized sheets. The values of the modulus of elasticity in compression shown in Table III are lower than the tensile modulus normally reported for wrought tungsten. Additional analyses will be made of the compression properties after the additional compression evaluations and the room-temperature tensile evaluations have been completed.

C. Bend Properties

Evaluation of the bend properties for both the longitudinal and transverse directions of the 0.060 in. thick tungsten sheet in the optimum condition has been completed.

The fixture, which is shown in Figure 10, and the procedures used for these evaluations conform to the recommendations in MAB-192-M. Figure 11 shows a drawing of the bend specimen. The specimen and the fixture were heated by tungsten-element radiation lamps, which were controlled by No. 36 gage chromel-alumel thermocouples flash welded to the underside of the specimen. Thermocouples attached to the punch were used to measure and control the temperature of the punch tip. A mirror, which was positioned under the specimen between the anvils of the fixture, was used to observe the surface of the specimen during bending. The bend angle at the first indication of fracture was calculated from the geometry of the fixture and the displacement of the punch when fracture was first noted. As a further check, the surface of the specimens that were bent 90 degrees without apparent fractures were examined with a magnifying glass to determine if fine cracks which could not be seen without magnification existed. In only one case were fine cracks observed,indicating that when cracks are initiated they proprogate and cause fracture. Consequently, the tungsten specimens were generally either bent 90 degrees without any sign of fracture or fractured completely during bending.

The initial bend-transition temperature evaluations were conducted on both transverse and longitudinal orientations of the 0.060 in. thick tungsten sheet with a punch having a radius of 0.090 in. or 1.5 times the sheet thickness (1.5t). Tables IV and V show for the longitudinal and transverse orientations respectively, the bend angle under load at fracture, the bend angle after springback, and the spring-back angle for each specimen evaluated. Figures 12 and 13 show the bend angle under load plotted as a function of temperature for longitudinal and transverse orientations respectively. Although there is appreciable scatter in the data within each sheet, the bend-transition temperature in both orientations was progressively higher for sheets 15, 17, and 6. The summary below shows for each different sheet and orientation the bend-transition temperature range based on the lowest temperature at which a 90-degree bend was accomplished and the highest temperature at which fracture occurred before a 90-degree bend was accomplished.

Sheet No.	Bend-Transition Temperature - °F[1] Longitudinal Direction	Transverse Direction
15	350-400	337-350
17	400	512-525
6	425-450	550-625

[1] Punch radius - 0.090 in. (1.5t)

A series of bend tests with punches of different radii up to 10t (0.60 in.) was conducted in an attempt to establish the minimum bend radius at room temperature for the 0.060 in. thick sheet in the longitudinal direction for the optimum condition. The maximum bend angle which could be made at room temperature with an 0.60 in. radius punch was 15 degrees. With punches of smaller radii the maximum bend angle at room temperature was lower. A decision was made to use the remaining bend specimens in the optimum condition from the longitudinal direction to establish the bend-transition temperature with a larger punch radius. The punch radius selected for these evaluations was 0.48 in. or 8t. Table VI and Figure 14 show the results of a series of bend evaluations on longitudinal specimens from sheets 15 and 17 at different temperatures. Using the same criterion discussed above, the bend-transition temperatures with an 8t radius punch for these sheets in the longitudinal direction are:

Sheet No.	Bend-Transition Temperature - °F[1]
15	250 - 275
17	400 - 425

[1] Punch radius - 0.48 in. (8t).

It is apparent that the bend-transition temperature for sheet 15 decreased about 100° F as the punch radius was increased from 1.5t to 8t whereas the bend-transition temperature of sheet 17 was unchanged for the same increase in the punch radius. The bend properties of the tungsten sheet will be discussed in greater detail after the scheduled evaluations on the recrystallized sheet are completed.

EVALUATION OF COATED MATERIALS

On the recommendation of the Refractory Metal Sheet Rolling Panel the evaluation of coated tungsten sheet has been eliminated from the program, and the evaluation of coated TZM sheet has been increased. At a meeting during September with representatives of BuWeps, the Air Force, the University of Dayton and SRI, arrangements were made to coordinate the evaluation of coated TZM on this program with the Air Force program on coatings at the University of Dayton Research Institute, who will arrange for the application of the coatings on all the specimens and will conduct the static oxidation tests on the TZM sheet with equipment they have available. The two coatings selected for evaluation are W-3 (Chromalloy) and PFR-6 (Pfaudler). The two coatings will be applied to the TZM sheet as soon as it is received and the specimens are machined.

FUTURE WORK

During the next reporting interval we expect to complete most of the remaining mechanical property evaluations on the tungsten sheet with the exception of the weld-joint-efficiency evaluations which will be deferred until the TZM materials are available. Assuming that the TZM sheet will be available in the near future, we expect to begin preparation of the specimens and the determination of the recrystallization temperature.

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3. Defense Metals Information Center Report 46D, September, 1958.

Table I

The Hardness and Percent Recrystallization of Three 0.060 In. Thick Tungsten Sheets[1] After Holding at Different Temperatures for Five and Sixty Minutes[2]

Specimen No.	Time at Temp. Min.	Temp. °F	Rc Hardness[3]	DPH[4]	Estimated Recrystallization %
Sheet No. 15					
C-15	As-Received		42.8	443	-
A-15	5	1800	42.8	-	-
B-15	5	2000	43.1	-	-
D-15	5	2200	42.7	-	-
E-15	5	2400	42.6	440	1
U-15	5	2425	43.8	-	-
P-15	5	2500	42.4	438	10
V-15	5	2525	41.1	427	15
S-15	5	2550	39.7	413	30
X-15	5	2575	37.5	388	75
F-15	5	2600	36.7	372	90
G-15	5	2800	35.6	362	100
H-15	5	3000	34.6	359	-
I-15	60	1800	44.4	458	-
J-15	60	2000	43.7	443	-
K-15	60	2200	42.6	439	2
L-15	60	2400	41.6	422	40
T-15	60	2425	38.6	389	80
R-15	60	2450	36.1	367	100
Q-15	60	2500	36.3	364	-
M-15	60	2600	36.1	-	-
N-15	60	2800	36.1	363	-
O-15	60	3000	35.3	-	-
Sheet No. 17					
G-17	As-Received		43.4	-	-
A-17	5	2500	44.7	439	8
B-17	5	2575	41.6	362	75

Table I (Continued)

The Hardness and Percent Recrystallization of Three 0.060 In. Thick Tungsten Sheets[1] After Holding at Different Temperatures for Five and Sixty Minutes[2]

Specimen No.	Time at Temp. Min.	Temp. °F	Rc Hardness[3]	DPH[4]	Estimated Recrystallization %
Sheet No. 17 (Continued)					
C-17	60	2200	43.4	438	3
D-17	60	2400	36.9	463	77
E-17	60	2425	38.1	356	90
F-17	60	2700	36.5	352	100
Sheet No. 6					
G-6	As-Received		42.7	-	-
A-6	5	2500	41.6	434	10
B-6	5	2575	39.6	414	60
C-6	60	2200	42.3	437	3
D-6	60	2400	38.7	373	60
E-6	60	2425	40.6	361	65
F-6	60	2700	32.7	350	100

[1] Sheet numbers 6, 15, and 17 from Fansteel Lot No. A5467. Specimen number suffix denotes sheet number.

[2] Specimens in optimum condition were resistance heated in a vacuum of 1×10^{-5} torr.

[3] Rc hardness measured on surface of the sheet.

[4] DPH at mid-thickness on a longitudinal section with a 3 Kg load.

Table II

The Hardness and Percent Recrystallization of 0.100 In. Thick Tungsten Sheet[1] After Holding at Different Temperatures for Five and Sixty Minutes[2]

Specimen No.	Time at Temp. Min.	Temp. ° F	Rc Hardness[3]	DPH[4]	Estimated Recrystallization %
K	As-Received		41.7	438	1
B	5	1800	43.9	485	1
C	5	2000	43.9	466	1
D	5	2200	43.8	462	1
Y	5	2300	42.0	-	-
E	5	2400	41.8	458	5
L	5	2500	40.2	433	20
F	5	2600	37.4	378	95
Z	5	2700	35.0	361	100
G	5	2800	35.0	359	-
N	5	2900	33.7	-	-
H	5	3000	33.8	-	-
I	5	3200	33.6	359	-
O	60	1900	41.9	449	5
P	60	2100	41.0	445	5
Q	60	2300	40.9	441	10
U	60	2400	38.3	388	60
R	60	2500	34.6	347	100
V	60	2600	34.3	344	-
S	60	2700	33.7	346	-
W	60	2800	33.2	346	-
T	60	2900	33.6	349	-
X	60	3000	33.0	344	-

[1] Sheet No. 112 from Fansteel Lot No. A 5467.

[2] Specimens in optimum condition were resistance heated in a vacuum of 1×10^{-5} torr.

[3] Rc hardness measured on surface of the sheet.

[4] DPH at mid-thickness on a longitudinal section with a 3 Kg load.

Table III

Longitudinal and Transverse Compression
Properties of 0.060 In. Thick Tungsten Sheets
In the Optimum Condition at Room Temperature

Orientation	Sheet No.	Specimen No.	0.2% Offset Yield Strength Ksi	Modulus of Elasticity 10^6 Psi
Long.	15	101	190.6	45.4
Long.	15	102	191.2	42.6
Long.	17	404	186.4	42.1
Average			189.4	43.4
Trans.	15	139	219.0	43.2
Trans.	17	442	209.6	42.0
Trans.	17	441	210.8	46.6
Average			213.1	43.9

Table IV

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction for 0.060 In. Thick Tungsten Sheet[1,2] - In the Optimum Condition - Punch Radius 0.090 In. (1.5 xSheet Thickness)

Sheet No.	Specimen No.	Evaluation Temp. ° F	Bend Angle Under Load at Fracture[3]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
6	205	375	13	-	-
6	198	400	21	-	-
6	203	400	8	-	-
6	204	425	27	-	-
6	216	425	12	-	-
6	199	450	94+	87	7
6	217	450	88	-	-
6	196	500	94+	87	7
6	197	525	92+	80	12
6	195	600	95+	87	8
15	76	325	6	-	-
15	77	350	95+	94	1
15	78	375	99+	92	7
15	75	388	95+	90	5
15	79	400	102+	92	10
15	55	400	30	-	-
15	62	425	97+	90	7
15	74	425	100+	93	7
15	63	450	85+	79	6
15	59	500	90+	84	6
15	57	525	90+	84	6
15	60	550	98+	91	7
15	56	600	89+	82	7
17	374	300	9	-	-
17	375	325	3	-	-
17	376	350	8	-	-
17	360	375	8	-	-
17	378	375	9	-	-

Table IV (Continued

Data for Determination of the Bend-Transition Temperature In the Longitudinal Direction for 0.060 In. Thick Tungsten Sheet[1,2] In the Optimum Condition - Punch Radius 0.090 In. (1.5 x Sheet Thickness)

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
17	357	400	24	-	-
17	355	400	49	-	-
17	373	400	97+	91	6
17	362	425	88+	82	6
17	358	500	86+	80	6
17	359	550	93+	87	6

[1] Fansteel Lot No. A 5467

[2] Specimens were heated in air, held 5 min. at temperature, and evaluated at a ram rate of 1.0 in./min.

[3] Plus (+) after bend angle denotes that specimen did not fracture.

Table V

Data for Determination of the Bend-Transition Temperature In the Transverse Direction for 0.060 In. Thick Tungsten Sheet[1,2] In the Optimum Condition - Punch Radius 0.090 In. (1.5 x Sheet Thickness)

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
6	243	500	7	-	-
6	259	525	7	-	-
6	260	550	18	-	-
6	241	550	104+	99	5
6	261	575	26	-	-
6	262	587	103+	97	6
6	258	600	103+	97	6
6	244	600	24	-	-
6	238	600	8	-	-
6	247	612	104+	98	6
6	242	625	104+	97	7
6	240	625	14	-	-
6	246	637	102+	96	6
6	245	650	110+	103	7
6	239	700	101+	95	6
15	115	300	10	-	-
15	112	325	5	-	-
15	133	325	6	-	-
15	114	337	104+	97	7
15	109	350	104+	96	8
15	131	350	6	-	-
15	126	362	101+	94	7
15	135	400	101+	95	6
15	108	400	72	-	-
15	110	400	11	-	-
15	111	450	108+	102	6
15	107	500	99+	92	7
15	113	600	92+	85	7
15	106	600	98+	92	6

Table V (Continued)

Data for Determination of the Bend-Transition Temperature In the Transverse Direction for 0.060 In. Thick Tungsten Sheet[1,2] In the Optimum Condition - Punch Radius 0.090 In. (1.5 x Sheet Thickness)

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
17	412	400	8	-	-
17	410	400	10	-	-
17	409	450	13	-	-
17	411	475	7	-	-
17	416	475	7	-	-
17	413	500	43	-	-
17	414	500	33	-	-
17	429	500	50	-	-
17	430	512	100+	94	6
17	428	525	102+	96	6
17	415	525	10	-	-
17	417	550	104+	98	6
17	408	600	103+	98	5

[1] From Fansteel Lot No. A 5467.

[2] Specimens were heated in air, held 5 min. at temperature, and evaluated at a ram rate of 1.0 in./min.

[3] Plus (+) after bend angle denotes that specimen did not fracture.

Table VI

Data for Determination of the Bend-Transition Temperature In the Longitudinal Direction for 0.060 In. Thick Tungsten Sheet[1,2] In the Optimum Condition - Punch Radius 0.48 In. (8 x Sheet Thickness)

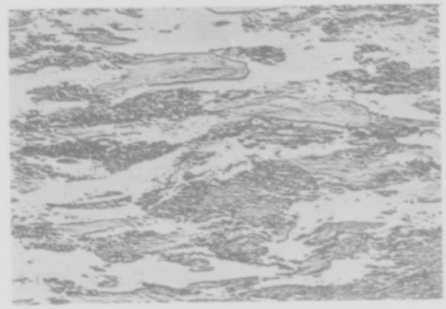
Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
15	87	200	1	-	-
15	89	225	10	-	-
15	90	237	12	-	-
15	88	250	122+	107	15
15	80	262	10	-	-
15	82	275	25	-	-
15	86	300	118+	104	14
17	385	300	7	-	-
17	386	350	6	-	-
17	389	375	22	-	-
17	388	387	21	-	-
17	387	400	122+	108	14
17	382	412	37	-	-
17	381	425	19	-	-

[1] From Fansteel Lot No. A 5467

[2] Specimens were heated in air, held 5 min. at temperature, and evaluated at a ram rate of 1.0 in./min.

[3] Plus (+) after bend angle denotes that specimen did not fracture.

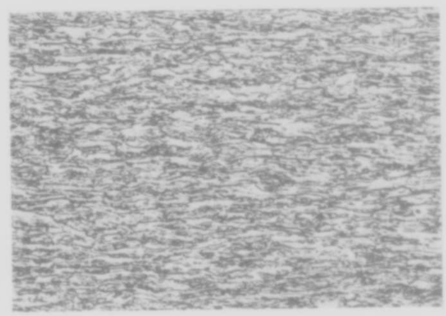
Longitudinal



Transverse

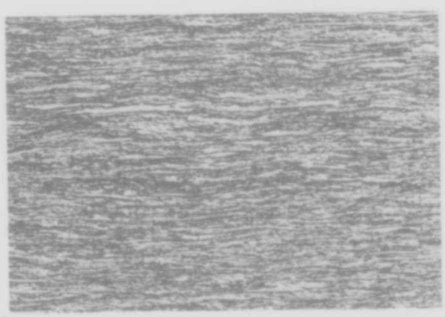
Sheet No. 6

Longitudinal

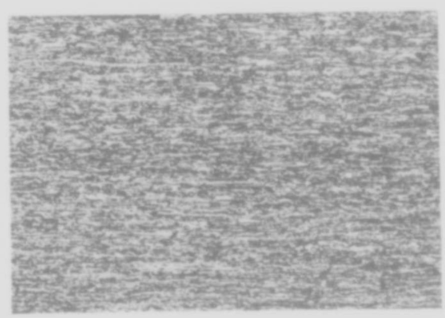


Transverse

Sheet No. 15



Longitudinal



Transverse

Sheet No. 17

Figure 1. The microstructure in longitudinal and transverse orientations of the 0.060-in. thick tungsten sheet in the optimum condition supplied for the investigation.

Magnification: 100X Etchant: $K_3Fe(CN)_6$

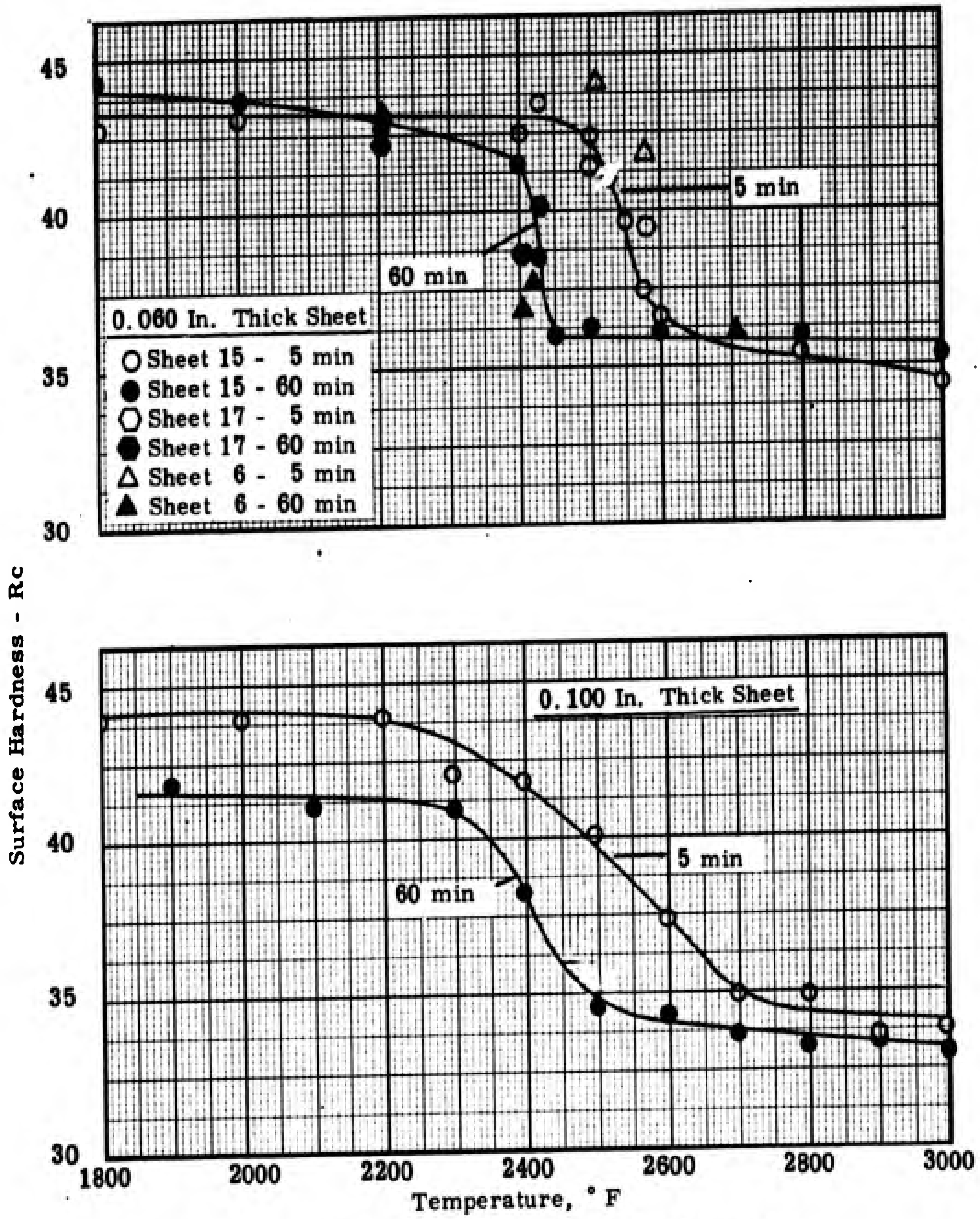


Figure 2. The Rc hardness of 0.060 and 0.100 in. thick tungsten sheet after holding 5 and 60 min at different temperatures.

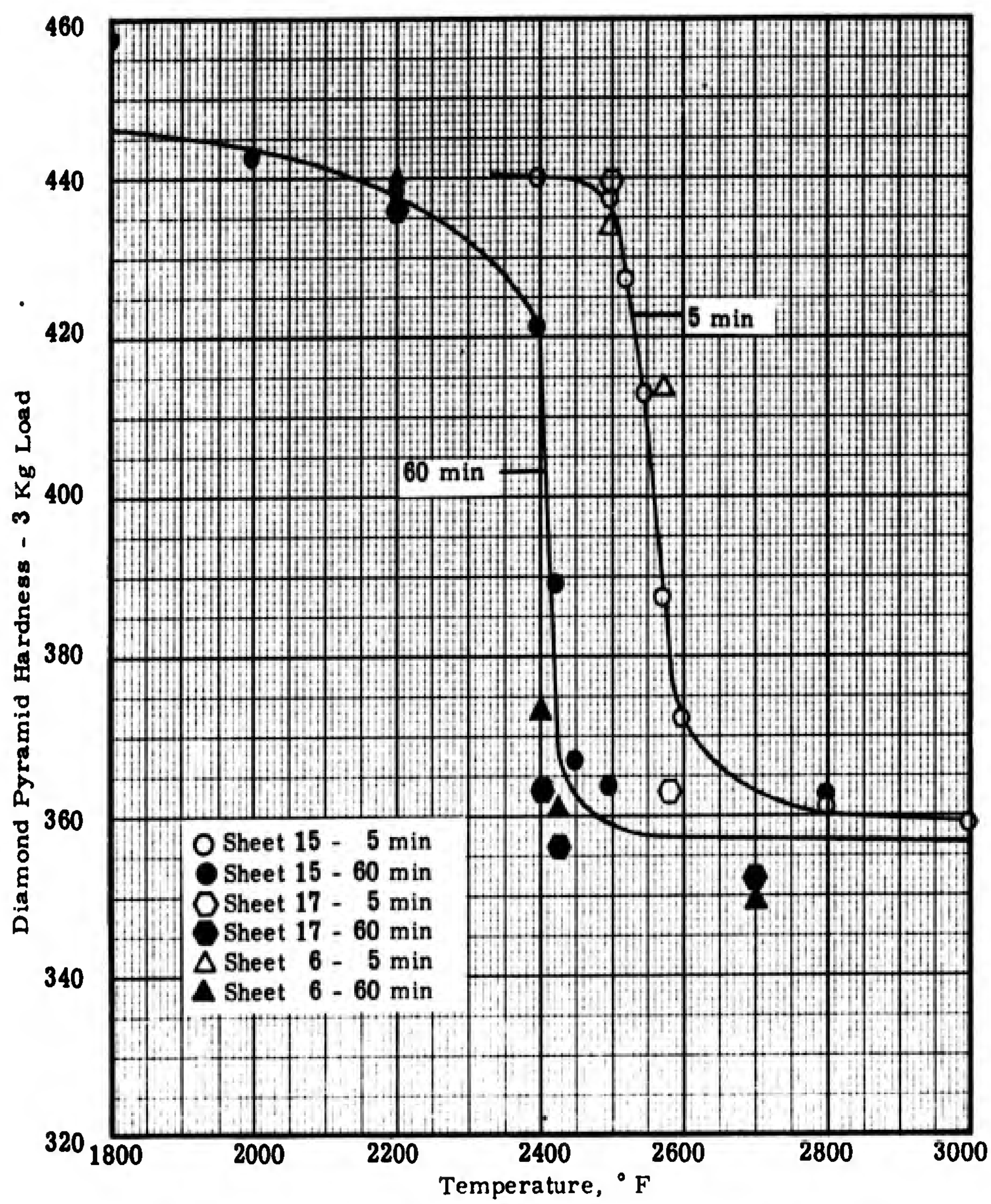


Figure 3. The DPH at the mid-thickness on longitudinal sections of different 0.060 in. thick tungsten sheet after holding 5 and 60 min at different temperatures.

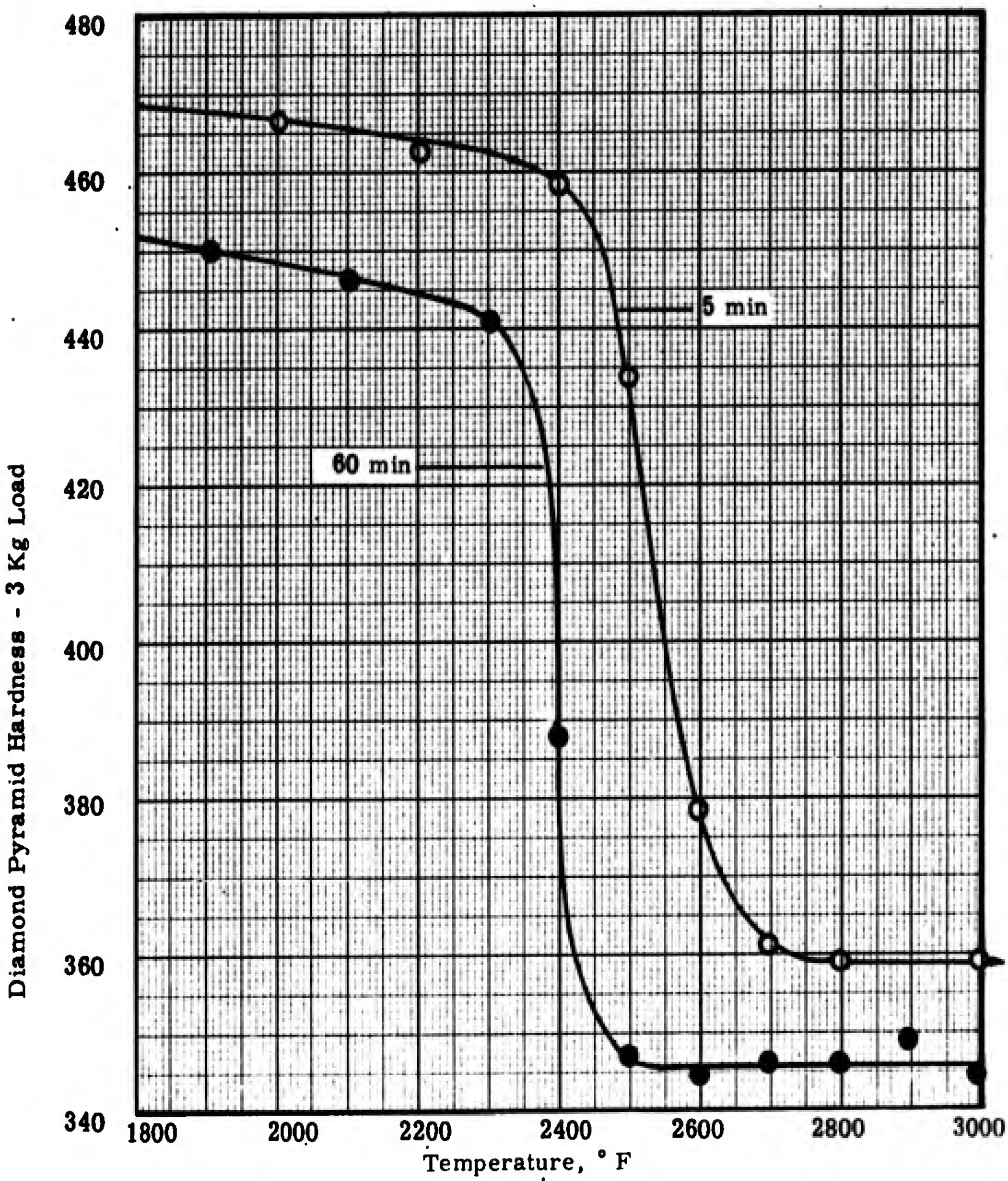


Figure 4. The DPH at mid-thickness on longitudinal sections of 0. 100 in. thick tungsten sheet after holding 5 and 60 min at different temperatures.

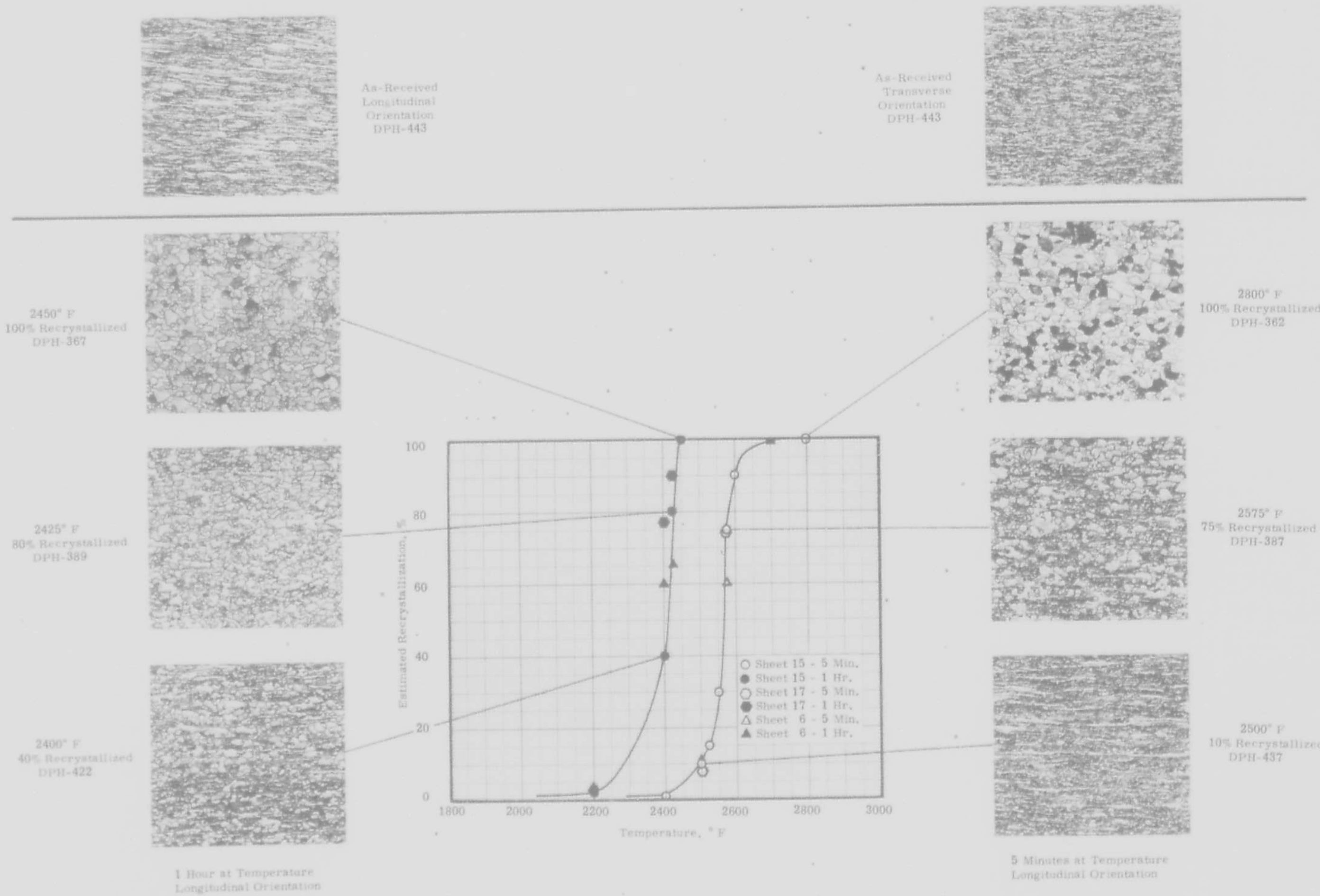


Figure 5. Effect of temperature and time at temperature on the recrystallization of 0.060 in. thick tungsten sheet.
Photomicrographs: Magnification 100X; Etchant - $K_3Fe(CN)_6$.

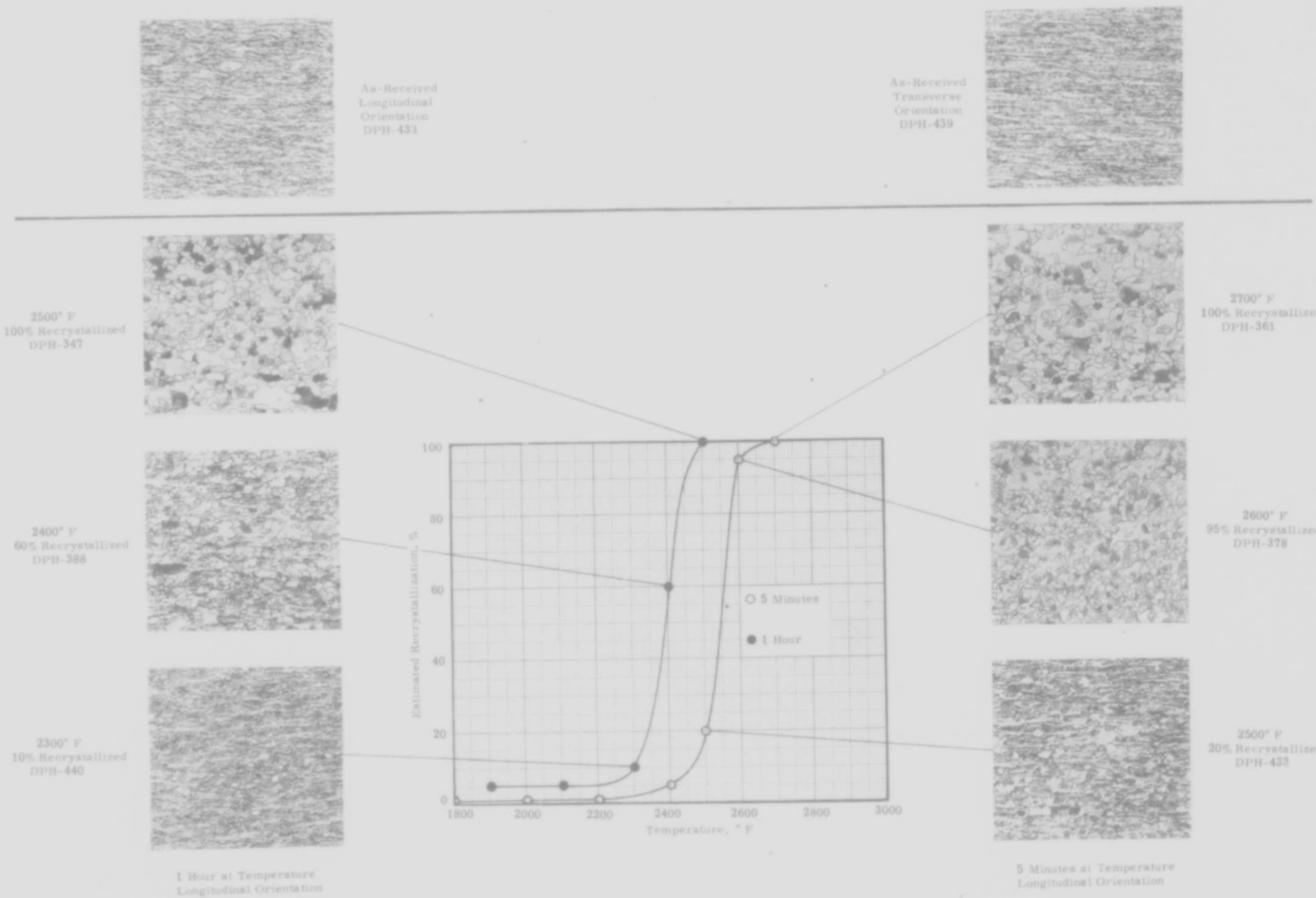
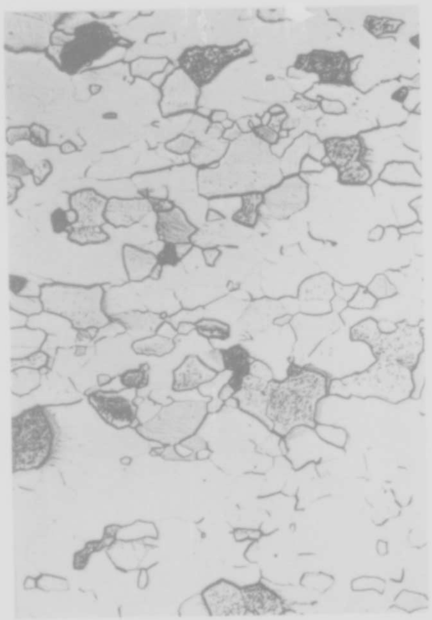
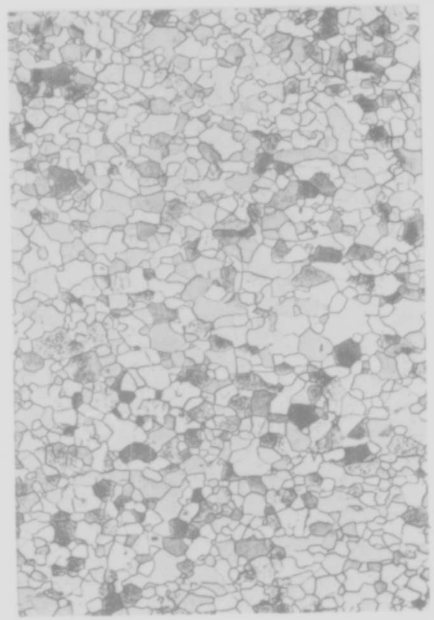


Figure 6. Effect of temperature and time at temperature on the recrystallization of 0.100 in. thick tungsten sheet.
Photomicrograph: Magnification 100X; Etchant - $K_3Fe(CN)_6$.



Sheet No. 6



Sheet No. 15

Sheet No. 17

Figure 7. Comparison of the longitudinal microstructure of the three 0.060-in. thick tungsten sheets after recrystallization at 2700° F for 60 min.

Magnification: 100X

Etchant: $K_3Fe(CN)_6$

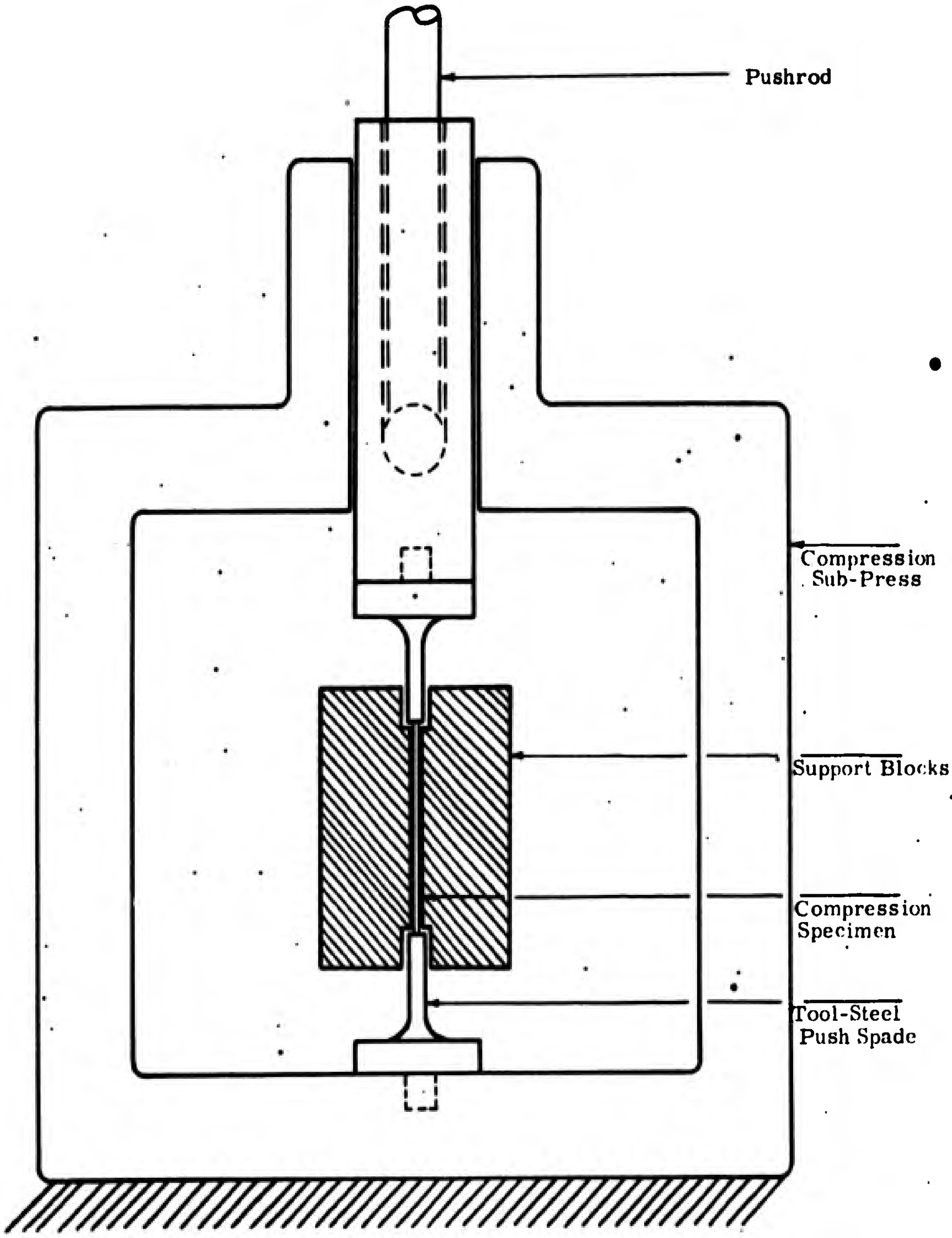


Figure 8. Compression fixture showing cross-section of the support blocks with specimen in place.

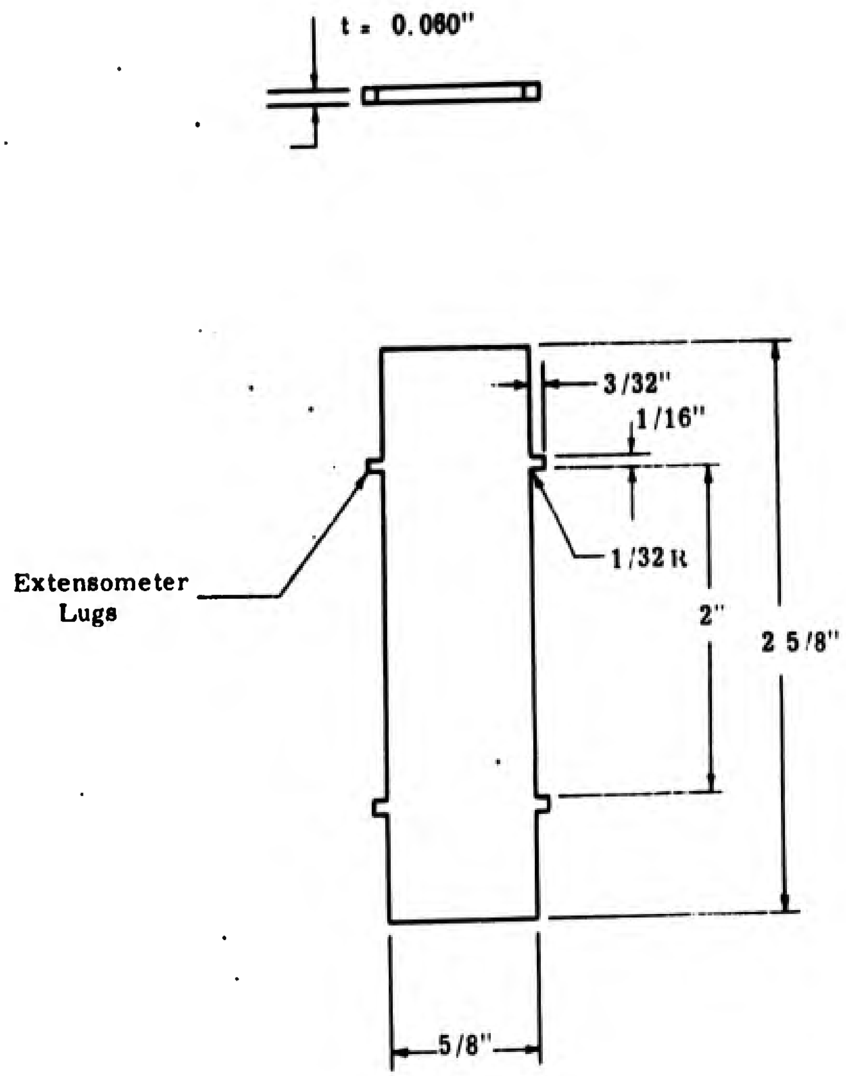


Figure 9. Compression specimen configuration.

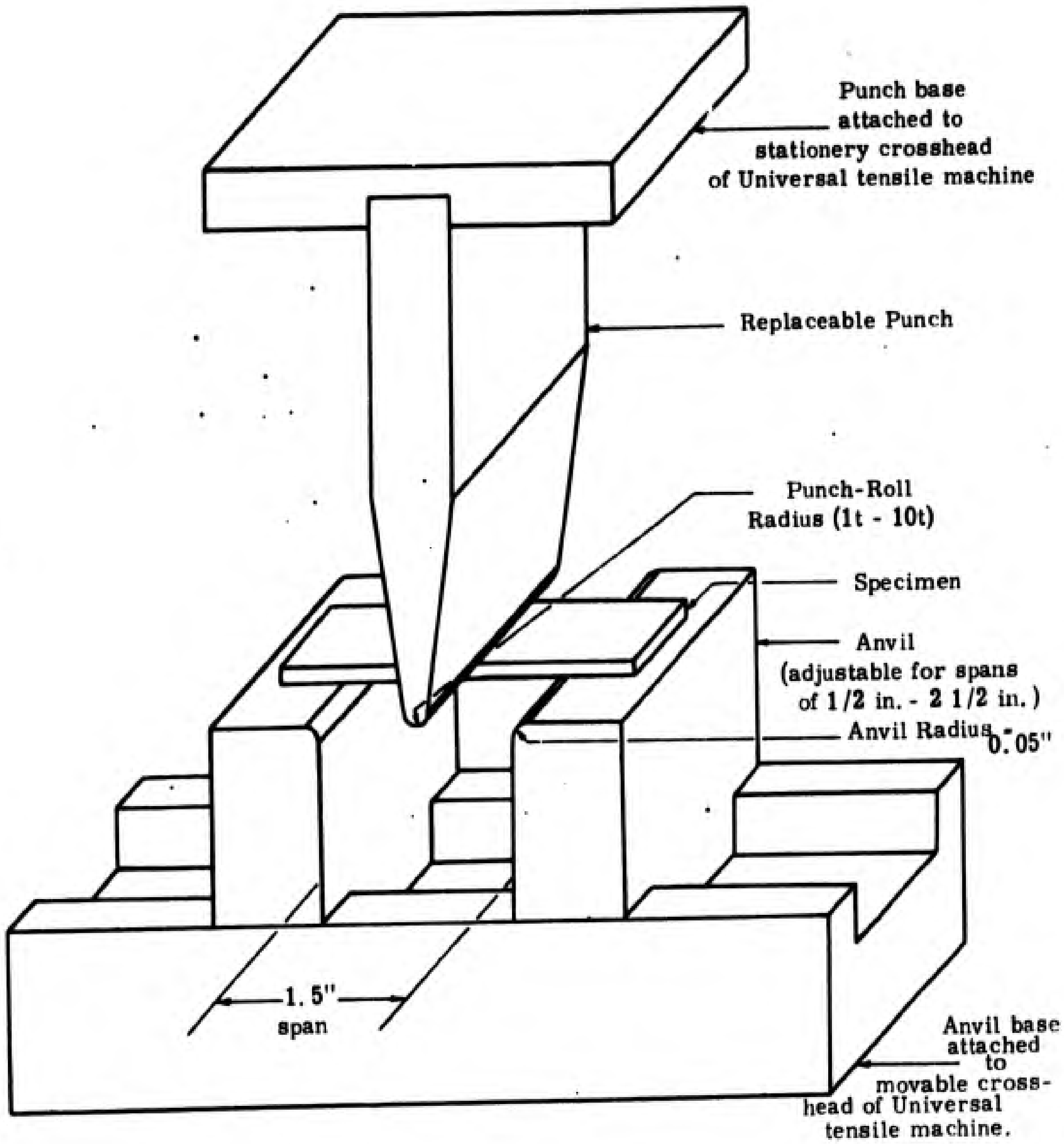


Figure 10. Bend test fixture.

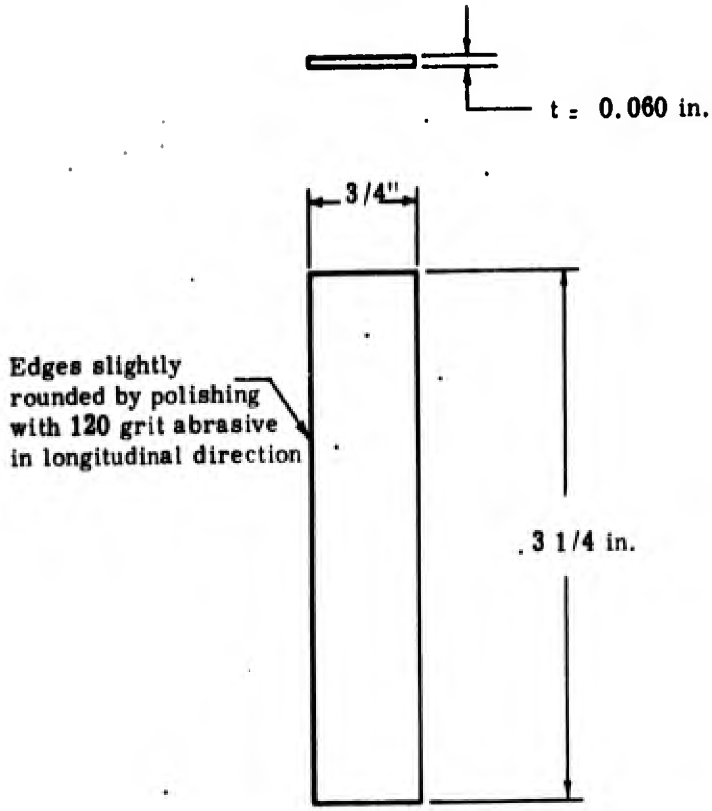


Figure 11. Bend specimen.

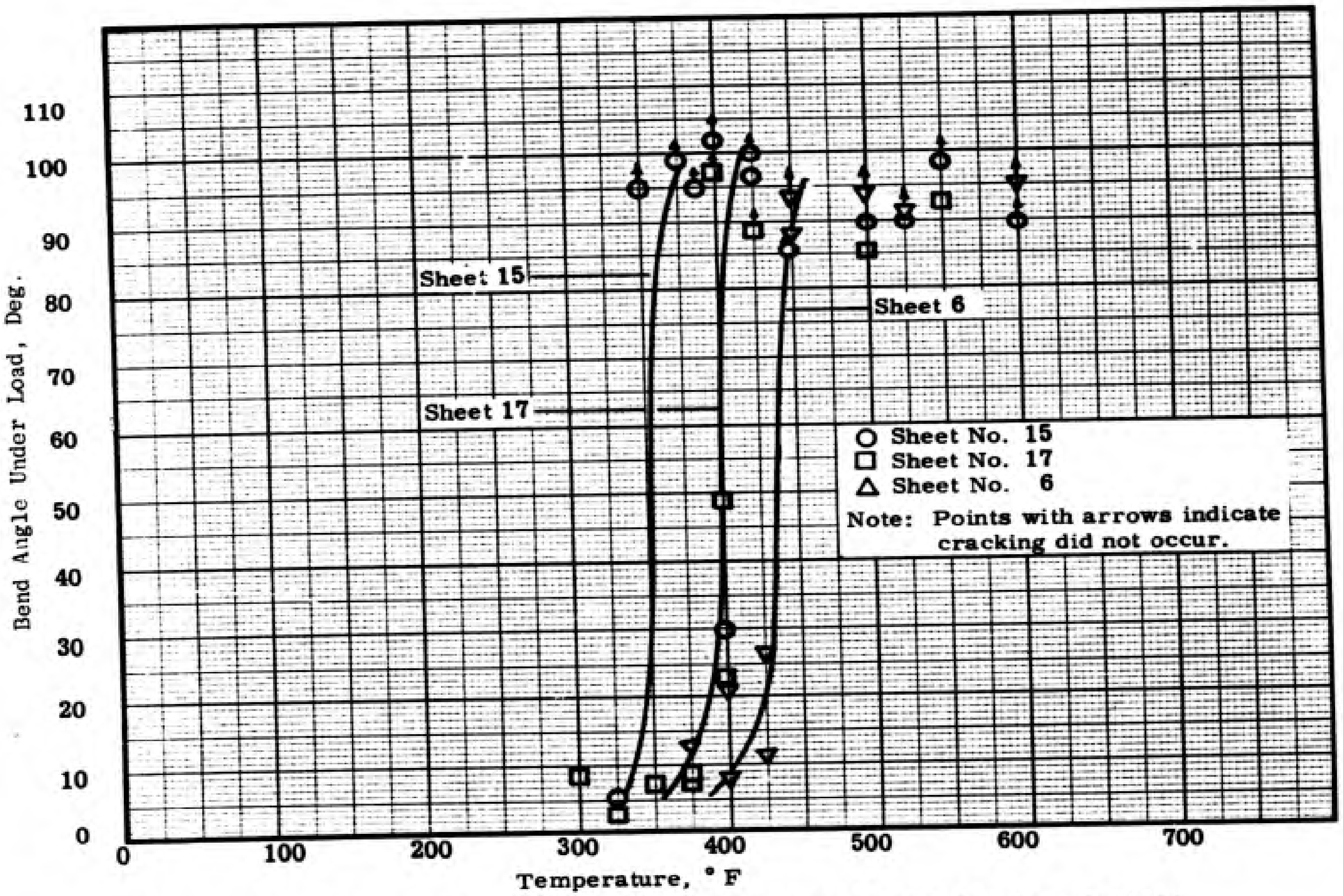


Figure 12. Bend-transition-temperature curves based on bend angle under load for the longitudinal orientation of three 0.060 in. thick tungsten sheets in the optimum condition using a punch with a radius of 1.5t, a span of 1.5 in., and a ram-rate of 1.0 in./min.

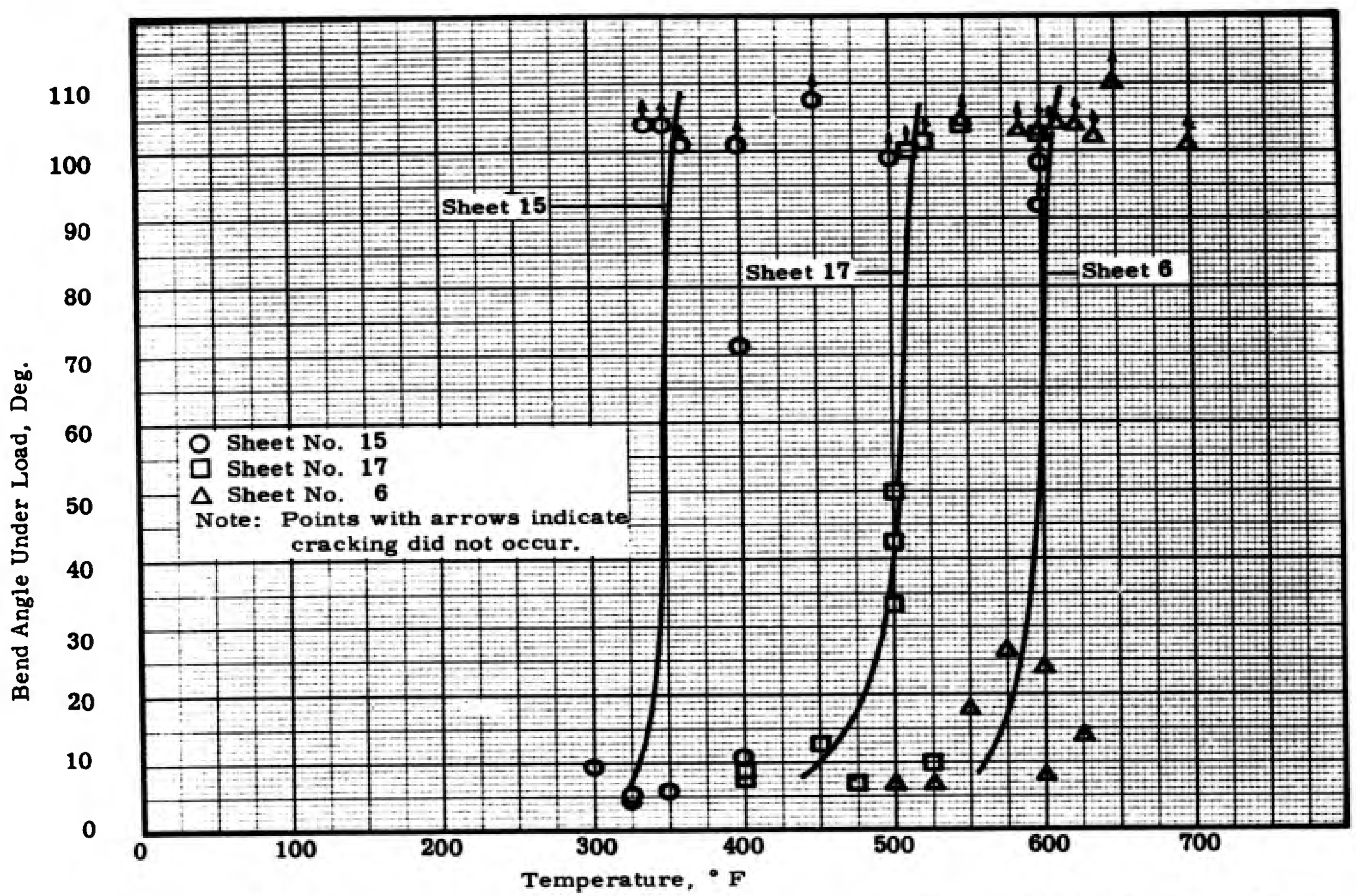


Figure 13. Bend-transition-temperature curves based on bend angle under load for the transverse orientation of three 0.060 in. thick tungsten sheets in the optimum condition using a punch with a radius of 1.5t, a span of 1.5 in., and a ram-rate of 1.0 in. /min.

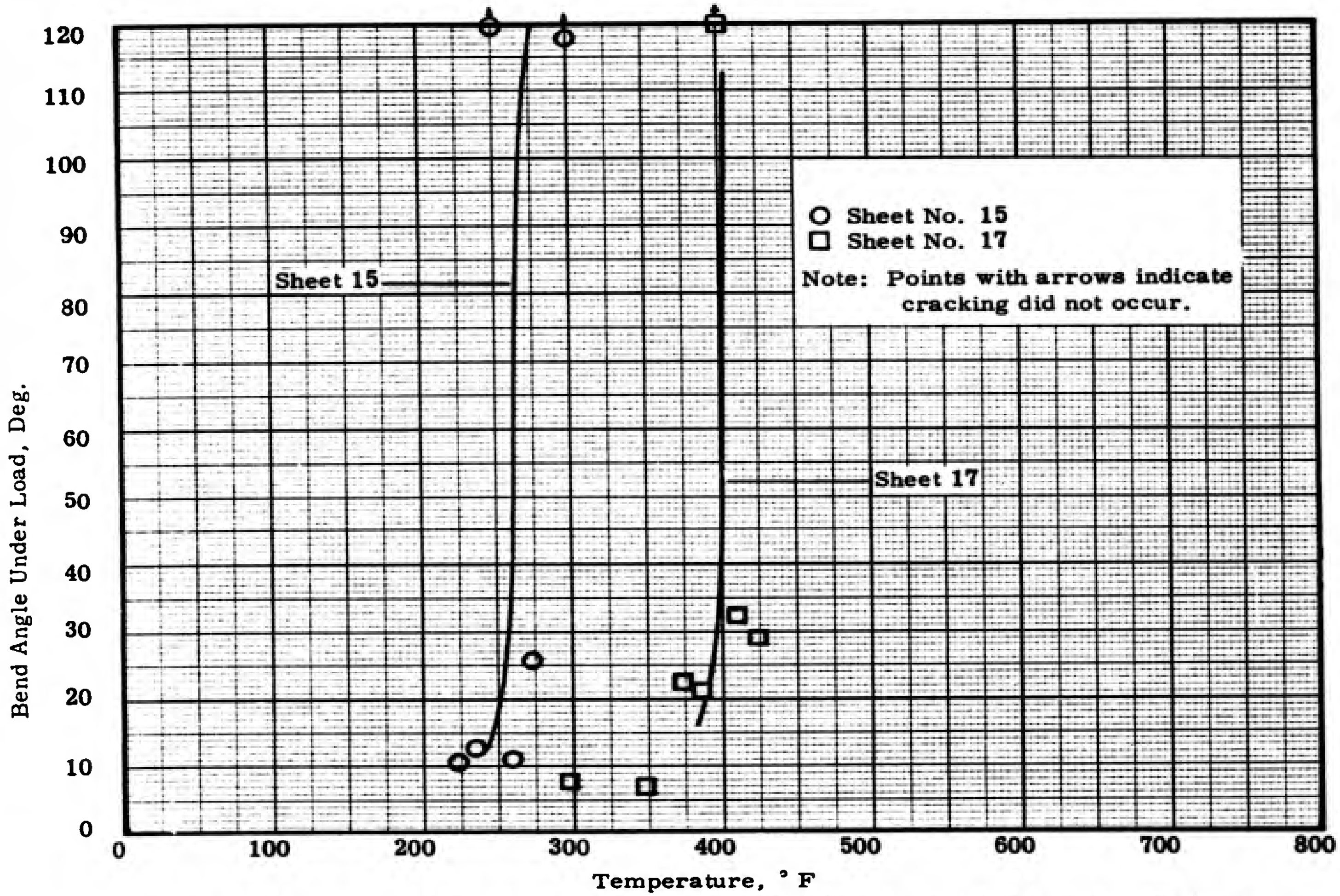


Figure 14. Bend-transition-temperature curves based on bend angle under load for the longitudinal orientation of two 0.060 in. thick tungsten sheets in the optimum condition using a punch with a radius of 8t, a span of 1.5 in., and a ram-rate of 1.0 in. /min.

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