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

February 28, 1964

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

Fifth Quarterly Progress Report

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Southern Research Institute
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Fifth Quarterly Progress Report on

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

INTRODUCTION

This is the fifth 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 Rolling Program. The tungsten sheet was produced by Fansteel Metallurgical Corporation under Bureau of Naval Weapons (BuWeps) Contract No. NOw-60-0621-c. The TZM molybdenum alloy sheet was produced by Universal-Cyclops Steel Corporation under Navy Contract NOas 59-6142c. The work described in this progress report was performed during the period from November 1, 1963 through January 31, 1964.

The experimental work that has been performed on the program so far has been limited to the tungsten sheet because the TZM sheet was not received until the middle of January, 1964.

In the previous progress reports we reviewed the scope and purpose of the program, and described in detail the experimental procedures and equipment that would be used. In our last progress report, for August, September, and October, 1963, we presented the results of the recrystallization-temperature determinations on tungsten, compression evaluations in the longitudinal and transverse orientations on tungsten sheet in the optimum condition and bend-property evaluations on the sheet in the optimum condition for punch radii of 1.5 T and 8 T.

During the period which this report covers, we have continued with the preparation of specimens from the tungsten sheet materials, conducted the compression and bend evaluations on the sheet in the recrystallized condition, completed additional bend evaluations on tungsten sheet in the optimum condition, performed tensile evaluations at room temperature and up to 2000° F on the tungsten sheets in the optimum condition, and begun the room-temperature shear-strength determinations. The required specimen blanks for all of the scheduled evaluations on the TZM have been sheared from two of the sheet thicknesses to be evaluated. Arrangements were made with Universal-Cyclops to fabricate 14 each fusion- and spot-welded specimens of the TZM and tungsten materials.

Conducting the additional bend evaluations on the tungsten sheet, which were requested by the Refractory Metal Sheet Rolling Panel (RMSRP), and mechanical difficulty with our vacuum-testing apparatus, which has now been repaired, delayed accomplishment of all of the experimental work outlined in our last progress report. In general, however, the experimental program is proceeding satisfactorily.

MATERIALS AND SPECIMENS

A. Tungsten Sheet

The description and processing of the tungsten sheets and location of the required specimen blanks for all the scheduled evaluations among the different tungsten sheets were reviewed in our third and fourth progress reports. Specimens for the determination of the compression and bend properties in the recrystallized condition were returned from "Ipsenlab" where they had been recrystallized in vacuum by holding 60 minutes at 2550° F. Rc hardness measurements verified that the specimens were heat treated as we had specified.

All of the tungsten specimens for the program have been machined, except the notch-tensile specimens, which have been purposely delayed until trials are completed of the notched-specimen design recommended in MAB 192-M.

B. TZM Sheet

The TZM sheet materials, which were produced by Universal-Cyclops Steel Corporation on Navy Contract No. NOas 59-6142c, were received on 9 January. The size and identification of each sheet is shown in Table I.

Table I

Identification and Size of the TZM Sheets

Sheet No.	Universal-Cyclops Lot No. [1]	Thickness in.	Length in	Width in.	Area. Sq. Ft.
55	10	0.037-0.043	64	24	10.68
56-1	10	0.037-0.043	$15\frac{7}{8}$	24	2.67
56-2	10	0.037-0.043	48	24	8.00
			Total		21.35
74	13	0.018-0.022	$12\frac{1}{2}$	$23\frac{7}{8}$	2.07
23	5	0.057-0.063	$12\frac{1}{2}$	24	2.08

[1] All of the different lots were from Heat No. KDTZM 1196.

A summary of the composition, manufacturing processes, and release properties for each TZM sheet was supplied for each sheet and gage by Universal-Cyclops and are shown in Tables XI through XIV. Briefly, the manufacturing process consisted of melting an 8 in. diameter ingot that was extruded to a $4\frac{1}{2}$ in. diameter ingot at 2100° F. The resulting ingot was then annealed for 1 hour at 2800° F and forged in "Infab" at 3400° F to 1.5-in.-thick sheet bars. The sheet bars were annealed at 2800°F for one hour and longitudinally rolled at 2200° F in two intermediate reductions and finally cross-rolled at 1800° F to within 4 to 8 mils of the final thickness. The sheets were annealed at 2700° F and 2150° F respectively after the first and second longitudinal rolling operations. Each gage was stress-relieved at 2300° F after cross-rolling and finished to the final thickness by belt grinding and pickling. Table II, on the following page, shows the chemistry of each sheet furnished for the evaluations.

Table II

Composition of TZM Materials Received For Property Evaluation

Sheet No.	Nominal Thickness in.	Lot No.	Element, %								
			C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
74	0.020	13	0.032	0.42	0.088	<0.0035	0.0018	<0.001	0.0042	0.0003	0.0001
35	0.040	10	0.030	0.49	0.104	<0.001	<0.0015	0.002	0.0012	0.0003	0.00017
56[1]	0.040	10	0.031	0.50	0.119	<0.0035	<0.0015	<0.001	0.0015	0.0002	0.00024
23	0.060	5	0.024	0.50	0.083	<0.0035	<0.0015	<0.001	0.0022	0.0010	0.0002

[1] Sheet No. 56 was received in two pieces labled 56-1 and 56-2. The chemistry is the same for both pieces.

As received at SRI, the sheets appeared to be in excellent condition and no serious surface defects were found by visual examination. The location of specimens for the three sheet thicknesses for all of the scheduled evaluations is shown in Figures 1 and 2. Specimen blanks from the 0.040 in. sheet for each different type of evaluation were divided equally between sheets 55 and 56. All of the specimen blanks from the 0.040-in.-thick and 0.020-in.-thick sheets have been cut. The blanks from the 0.020-in.-thick sheets were sheared at room temperature, while the blanks from 0.040-in-thick sheets were warm sheared after preheating to 550° F.

C. Spot and Fusion Welding of TZM and Tungsten Materials

Arrangements have been made with Universal-Cyclops for welding the tungsten and TZM on their Contract No. NOw63-0043c for the scheduled weld-joint evaluations. We are presently preparing to send to Universal-Cyclops sufficient 0.040-in-thick TZM and 0.060-in.-thick tungsten specimen blanks for the fabrication of 14 fusion-welded and 14 spot-welded specimens of each material for subsequent tensile evaluations. The specimens will be fabricated according to the general procedures given in MAB-192-M, pages 21-23. Since individual specimen blanks have already been cut from the tungsten sheet they will be supplied in this form. However, for the spot and fusion welds on the TZM, the materials will be supplied in $2\frac{1}{2}$ in. x $6\frac{3}{8}$ in. and $2\frac{1}{4}$ in. x $6\frac{3}{8}$ in. sections respectively, which will be welded and subsequently cut into specimens by SRI.

EXPERIMENTAL PROCEDURES AND RESULTS

A. Tensile Evaluations of Tungsten Sheet

Room-temperature tensile evaluations in the longitudinal and transverse orientations and elevated-temperature tensile evaluations up to 2000° F in the longitudinal orientation have been completed on the 0.060 and 0.100-in.-thick tungsten sheets in the optimum condition. The specimens were evaluated in accordance with the general conditions specified in MAB-192-M. Sketches of the specimen configurations for the room-temperature and elevated-temperature evaluations are shown in Figures 3 and 4.

Results of the tensile evaluation of the 0.060 and 0.100-in.-thick tungsten sheet are given in Tables III and IV respectively, which show that for comparable orientations and temperatures the tensile properties of the two gages are about equal. The results also show that the strength properties at room temperature for both thicknesses are generally lower for the longitudinal direction (190 to 208 ksi UTS) than for the transverse orientation (213 to 218 ksi UTS) although the fracture of the transverse specimen from 0.060-in.-thick sheet No. 17 was completely brittle, causing the apparent strength to be lower than that of other sheets. The smooth-tensile-transition temperature for the longitudinal orientation of the 0.060 in. sheet is apparently below 1200° F - the ductility increased significantly between room temperature and 1200° F but did not increase appreciably between 1200 and 2000° F. A direct comparison of the tensile properties given in Tables III and IV to those reported by Fansteel (1)[1] is not possible because the sheets, orientations, or temperatures were not comparable. In general, however, the tensile strength properties at 1200 and 2000° F given in our report appear to be lower than the average strength properties, but within the range, reported by Fansteel for the material. Since Fansteel did not report tensile results at room temperature we can not compare results. In general, however, the room-temperature tensile properties given are comparable to data reported from other sources (2).

B. Compression Evaluations on Tungsten Sheet

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 and recrystallized conditions.

The specimen configuration, sketch of the fixture, qualification procedures for the apparatus, and general procedures were discussed thoroughly in our fourth quarterly progress report.

Results of the compression evaluations in both the optimum and recrystallized conditions are given in Table V. A definite drop-of-beam yield behavior was observed for the recrystallized sheet, and consequently the strength at the upper yield point was approximately 6.5 psi higher than at the 0.2% offset. The 0.2%-offset yield strength in compression is lower for the longitudinal orientation than for the transverse orientation in the optimum condition and approximately the same in the recrystallized condition. This difference in the yield strengths between the two orientations in the optimum condition is probably due to the stress reversal between

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[1] Numbers in parenthesis are for references in the Bibliography.

longitudinal rolling and compression testing in the longitudinal direction (the Bauschinger effect), which would cause the longitudinal yield strength to be lower than in the transverse direction. The yield strength in compression is approximately 45 ksi lower for the recrystallized condition than for the optimum condition in the longitudinal orientation and about 65 ksi lower in the transverse orientation. The data, shown in Tables V, also indicate that sheet No. 15 generally has the highest yield strength, and sheet No. 6 generally has the lowest yield strength, the difference being the greatest in the recrystallized condition. This difference in strength between the sheets is probably related to the differences in the as-received structures of the sheets, which were shown and reported in our fourth progress report. The structure of sheet No. 6 in the as-received condition was much coarser than that of sheets 15 and 17 and appeared to have had a larger grain size before working than the other sheets. The difference in grain sizes between the sheets was even more pronounced after recrystallization. Large grain size is generally detrimental to the room-temperature mechanical properties of metals.

The modulus of elasticity in compression in both orientations for the optimum condition was lower than for the recrystallized condition. In other evaluation programs we have observed low moduli in the transverse direction in compression tests of refractory metals after longitudinal drawing or rolling. In this case the modulus of the sheet in the optimum condition is relatively low in both orientations. Since the evaluations were conducted with the same apparatus and under the same conditions, and since the results are fairly consistent, we believe that the differences in modulus for the two conditions are real. The room-temperature tensile moduli for the optimum condition, shown in Table III, generally tend to fall between the compressive moduli levels for the two conditions.

C. Bend Properties on Tungsten Sheet

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

In our fourth progress report we reported the results of bend-transition-temperature evaluations, on both transverse and longitudinal orientations of the 0.060-in.-thick tungsten sheet in the optimum condition, made with a punch having a radius of 0.090 in., or 1.5 times the sheet thickness (1.5T). This bend radius was in accordance with our proposal. During the December, 1963 meeting, the RMSRP recommended that additional bend evaluations be conducted to determine the 4T bend-transition temperature, which is generally used in the refractory-metals industry although MAB-192-M does not specify that a particular punch radius be used. In accordance with the recommendation of the RMSRP, additional specimens were machined from the 0.060 in. tungsten sheet and the bend-transition temperature for a 4T punch was established. The apparatus and procedures, which were identical to those used in the previous evaluations, were discussed in detail in the fourth progress report. Part of the recrystallized bend specimens had been evaluated with the 1.5T punch before the RMSRP recommendation to use a 4T punch was received. The specimens which were bent with a 1.5T punch did not conform to the punch, but had the same actual radius of curvature (approximately 0.31 or 5T) as those subsequently bent with a 4T punch; consequently, data obtained with the 1.5T punch from recrystallized specimens is considered comparable to that obtained with a 4T punch. The 4T bend-transition-temperature data for the transverse and longitudinal orientations of the 0.060 in. tungsten sheet in the optimum and recrystallized conditions are shown in Tables VI through IX and plotted in Figures 5 and 6. The transition temperature ranges, which are summarized in the table below, are based on the minimum temperature at which a 90-degree bend was accomplished and the maximum temperature at which fracture occurred before a 90-degree bend was accomplished.

4T Bend Transition-Temperature Ranges (° F) for 0.060 in. Tungsten Sheet

Sheet No.	Optimum Condition		Recrystallized Condition	
	Long.	Trans.	Long.	Trans.
15	225-237	325-337	500-525	550-575
17	300-325	500-525	525-650	575-600
6	387-400	525-562	638-650	575-650

In the optimum condition the 4T transition temperature was from 100 to 200° F lower in the longitudinal direction than in the transverse direction. In the recrystallized condition the longitudinal 4T transition temperature was only about 50° F lower than for the transverse direction. In general, the 4T bend-transition temperature for the recrystallized material was about 200 to 300° F higher in the longitudinal direction and about 50 to 200° F higher in the transverse direction than that for optimum material, significant variations in these differences occurring among different sheets. Similar increases in the bend transition temperature after recrystallization have been reported in the literature (3).

Bend transition data for 1.5T and 8T bend-radii, as reported in a previous progress report, and the 4T bend data are included in the summary of bend transition temperatures given in Table X. This summary shows that the bend transition temperature for the longitudinal orientation of the optimum sheet was from 50 to 100° F lower for the 4T punch than for the 1.5T punch. For the transverse orientation of the optimum sheet there was not a significant change in the transition temperature for the 1.5T and 4T punches. The apparent bend-transition-temperature of sheets 15 and 17 in the longitudinal direction and the optimum condition was slightly higher for an 8T bend than for a 4T bend rather than logically lower. However, relatively few specimens were evaluated with the 8T punch which may account for the high apparent 8T bend-transition temperature. It is also possible that cracks were initiated at relatively low temperatures because of the increased area under high stress and the increased statistical probability of overstressing a potential fracture site.

We have approximately six untested longitudinal bend specimens representing the recrystallized condition of sheets 6, 15, and 17. We recommend that these specimens be evaluated with an 8T punch at different temperatures to provide further comparison of the recrystallized and optimum material conditions rather than for determination of the minimum bend radius as originally scheduled.

D. Shear Evaluations on Tungsten Sheet

Four shear specimens were machined (one each from sheet 6 and 17 and two from sheet 15) to the specimen configuration shown in MAB-192-M, page 10. Two of the specimens were evaluated at room-temperature in accordance with procedures given in MAB-192-M. Rather than failing in shear, these specimens exhibited brittle failure in tension at loads of 700 and 980 lb. The loads at fracture correspond to shear stresses of 59.5 and 84.8 ksi, however, it is probable that the ultimate shear stress is considerably higher. Since shear tests at room temperature appear to be impractical on brittle notch-sensitive materials, we propose to evaluate the two remaining shear specimens at a temperature slightly above the notched-transition temperature, which will be determined from results from the notched tensile tests.

E. Bearing Evaluations

Four bearing specimens, in accordance with the design shown in MAB-192-M, page 17, have been machined from the 0.060-in.-thick tungsten sheet. We anticipate that these specimens will fail in tension, similarly to the shear specimens, at room-temperature rather than in bearing as desired. Therefore, we propose to evaluate these specimens at a temperature slightly above the notched-transition temperature, rather than at room temperature as originally scheduled, after the appropriate temperature is established from the notched-tensile tests.

FUTURE WORK

A. Tungsten

During the next reporting period we expect to complete the tensile and notch-tensile evaluations in both the optimum and recrystallization conditions. Sufficient material, as outlined in the Materials and Specimens Section, for spot and fusion weld evaluations will be sent to Universal-Cyclops Steel Corporation for welding.

B. TZM Molybdenum Alloy

During the next reporting period we expect to machine the specimens for the different evaluations, complete the recrystallization studies, send trial-coating specimens to University of Dayton for subsequent coating, and begin the bend property evaluations.

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Table III

Tensile Properties[1] of the 0.060-In.-Thick Tungsten Sheets
In the Optimum Condition at Room[2] and Elevated Temperatures[6]

Specimen No.	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1.00 in. %	Reduction of Area %
6-150	Long.	RT	188.0	190.5	46.0	0.5	–[4]
17-295		RT	200.0	208.0	48.2	0.8	–[4]
15-2		RT	196.0	200.5	54.6	0.8	–[4]
Average			194.7	199.7	49.6	0.7	
15-136	Trans.	RT	216.1	218.5	52.5	0.5	–[4]
17-438		RT	–[3]	150.03[3]	51.6	–[3]	–[3]
Average			216.1	218.5	52.0	0.5	
15-4	Long.	1200	77.4	87.2	–[5]	7.2	61.0
6-141		1200	77.0	82.2	–[5]	7.1	51.0
Average			77.2	84.7		7.2	56.0
17-284	Long.	2000	62.7	66.0	–[5]	8.1	67.5
6-142		2000	59.0	62.2	–[5]	8.2	70.5
Average			60.8	64.3		8.2	69.0

[1] Evaluated at a strain rate of 0.005 in./in./min.
[2] Room temperature properties evaluated in both longitudinal and transverse directions; all other temperatures in the longitudinal direction.
[3] Brittle fracture - No 0.2%-offset yield strength, elongation or reduction of area recorded - ultimate not included in average.
[4] Too small to be measured.
[5] Modulus-of-elasticity not calculated; will be calculated and included in future results.
[6] Specimens were heated by radiation from tantalum elements in a vacuum of 5 x 10^{-6} torr.

Table IV

Tensile Properties[1] of the 0.100-In.-Thick Tungsten Sheets
In the Optimum Condition at Room[2] and Elevated Temperatures[5]

Specimen No.	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1.00 in. %	Reduction of Area %
112-8	Long.	RT	192.3	196.5	40.0	0.5	-[4]
112-9		RT	193.0	199.0	46.3	0.7	-[4]
Average			192.6	197.8	43.2	0.6	-
112-30	Trans	RT	212.0	213.5	53.4	0.5	-[4]
112-31		RT	212.5	217.0	49.1	0.6	-[4]
Average			212.2	215.2	51.2	0.6	
112-10	Long.	2000	63.2	68.2	-[3]	11.5	83.8
112-11		2000	63.2	67.2	-[3]	11.3	86.3
Average			63.2	67.7		11.4	85.0

[1] Evaluated at a strain rate of 0.005 in./in./min.
[2] Room temperature properties evaluated in both longitudinal and transverse directions; all other temperatures in the longitudinal direction.
[3] Modulus-of-elasticity not calculated; will be calculated and included in future results.
[4] Too small to be measured.
[5] Specimens were heated by radiation from tantalum elements in a vacuum of 5×10^{-6} torr.

Table V

Longitudinal and Transverse Compression Properties at Room Temperature of 0.060-In.-Thick Tungsten Sheet in the Optimum[1] and Recrystallized[2] Conditions

Orientation	Optimum Condition				Recrystallized Condition			
	Sheet No.	Spec. No.	0.2%-Offset Yld. Str. ksi	Mod. of Elasticity 10^6 psi	Sheet No.	Spec. No.	0.2%-Offset Yld. Str.[3] ksi	Mod. of Elasticity 10^6 psi
Long.	6	458	176.7	46.0	6	192	130.5	49.2
Long.	15	101	190.6	45.4	6	193	132.0	65.8
Long.	15	102	191.2	42.6	15	457	154.0	54.5
Long.	17	404	186.4	42.1	17	407	151.0	53.7
Average			186.2	44.0			141.9	55.8
Trans.	6	459	201.0	47.9	6	271	127.2	58.0
Trans.	15	139	219.0	43.2	6	273	127.0	55.8
Trans.	17	441	210.8	46.6	15	455	144.3	52.6
Trans.	17	442	209.6	42.0	17	456	160.5	55.5
Average			210.1	44.9			139.8	55.5

[1] Warm-rolled and stress-relieved at 2100° F.
[2] Recrystallized for 60 min at 2550° F.
[3] Upper field point approximately 6.5 psi higher than at 0.2% offset.

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 - 4T Punch Radius

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	467	300	17	-	-
6	465	325	25	-	-
6	461	350	64	-	-
6	463	375	58	-	-
6	466	375	21	-	-
6	464	388	109+	102	7
6	468	388	22	-	-
6	469	400	35	-	-
6	462	400	105+	99	6
6	460	450	106+	101	5
15	483	100	7	-	-
15	484	175	9	-	-
15	485	200	24	-	-
15	486	212	17	-	-
15	482	225	101+	94	7
15	487	225	64	-	-
15	488	238	20	-	-
15	489	238	74	-	-
15	481	325	99+	94	5
15	480	425	101+	96	5
17	509	225	15	-	-
17	501	250	15	-	-
17	508	275	26	-	-
17	502	300	25	-	-
17	507	300	36	-	-
17	504	312	41	-	-
17	505	312	65	-	-
17	503	325	105+	99	6
17	506	325	105+	98	7
17	500	350	105+	99	6

[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 VII

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 - 4T Punch Radius

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	479	475	88	-	-
6	471	500	16	-	-
6	478	512	16	-	-
6	477	525	106^{+}	100	6
6	472	550	69	-	-
6	475	550	74	-	-
6	474	562	105^{+}	100	5
6	476	562	24	-	-
6	473	575	106^{+}	101	5
6	470	600	103^{+}	98	5
15	491	250	16	-	-
15	492	300	22	-	-
15	494	312	36	-	-
15	495	312	34	-	-
15	493	325	107^{+}	99	8
15	496	325	62	-	-
15	497	338	31	-	-
15	498	338	110^{+}	102	8
15	490	350	106^{+}	99	7
15	499	375	108^{+}	100	8
17	510	400	6	-	-
17	511	400	21	-	-
17	513	450	34	-	-
17	514	475	13	-	-
17	515	488	20	-	-
17	512	500	110^{+}	103	7
17	516	525	16	-	-
17	518	525	14	-	-
17	519	538	108^{+}	102	6
17	517	550	110^{+}	103	7

[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 VIII

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction for 0.060-In.-Thick Tungsten Sheet[1,2] In the Recrystallized Condition - 4T Punch Radius[3]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[4] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	236	600	6	-	-
6	232	612	8	-	-
6	234	625	42	-	-
6	219	625	93	-	-
6	231	638	38	-	-
6	235	650	101+	96	5
6	218	650	102+	98	4
6	214	650	112+	106	6
6	215	662	104+	99	5
6	237	700	99+	94	5
15	64	400	4	-	-
15	70	425	5	-	-
15	66	450	6	-	-
15	67	475	7	-	-
15	69	488	7	-	-
15	65	500	99+	90	9
15	68	500	95	-	-
15	73	512	106+	94	12
15	72	525	9	-	-
15	81	525	4	-	-
15	71	550	107+	96	11
15	53	600	104+	95	9
15	91	600	107+	101	6
17	379	475	5	-	-
17	363	500	7	-	-
17	380	512	6	-	-
17	372	525	108+	98	10
17	364	550	82	-	-
17	365	550	65	-	-
17	366	575	30	-	-
17	396	625	103+	97	6
17	367	650	42	-	-
17	370	650	77	-	-
17	371	662	103+	97	6
17	395	662	105+	101	4
17	369	675	92+	88	4
17	368	700	94+	91	3

[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] Radius of curvature of bent specimens was approximately 5T.
[4] Plus (+) after bend angle denotes that specimen did not fracture.

Table IX

Data for Determination of the Bend Transition Temperature in the Transverse Direction for 0.060-In. -Thick Tungsten Sheet[1,2] In the Recrystallized Condition - 4T Punch Radius[3]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[4] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	256	500	3	-	-
6	254	550	6	-	-
6	266	550	6	-	-
6	257	562	78	-	-
6	265	562	72	-	-
6	255	575	107+	106	1
6	267	575	68	-	-
6	251	600	99+	97	2
6	250	625	110+	105	5
6	249	650	35	-	-
6	263	650	53	-	-
6	264	650	105+	101	4
15	117	500	7	-	-
15	127	525	7	-	-
15	128	538	4	-	-
15	129	538	43	-	-
15	134	550	5	-	-
15	118	550	85	-	-
15	125	550	102+	98	4
15	119	562	7	-	-
15	124	562	18	-	-
15	130	562	101+	96	5
15	132	575	104+	97	7
15	120	575	78	-	-
15	123	575	96+	94	2
15	122	588	95+	92	3
15	116	600	96+	94	2
15	121	650	95+	92	2
17	435	500	6	-	-
17	434	525	4	-	-
17	419	550	6	-	-
17	426	550	4	-	-
17	422	550	8	-	-
17	424	562	24	-	-
17	425	562	70	-	-
17	423	575	104+	97	7
17	432	600	25	-	-
17	420	600	101+	95	6
17	427	600	26	-	-
17	421	625	105+	97	8
17	433	625	105+	101	4
17	418	650	98+	94	4
17	431	650	108+	102	6

[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] Radius of curvature of bent specimens was approximately 5T.
[4] Plus (+) after bend angle denotes that specimen did not fracture.

Table X

Summary of Bend Data on 0.060-In.-Thick Tungsten Sheet

Punch	Sheet No.	Optimum Condition Long.	Optimum Condition Trans.	Recrystallized Condition Long.	Recrystallized Condition Trans.
1.5T	15	350-400	337-350	-	-
1.5T	17	400	512-525	-	-
1.5T	6	425-450	550-625	-	-
4T	15	225-237	325-337	500-525	550-575
4T	17	300-325	500-525	525-650	575-600
4T	6	387-400	525-562	650-638	575-650
8T	15	250-275	-	-	-
8T	17	400-425	-	-	-

Table XI

Summary of Composition, Manufacturing Process, and Release Properties for 0.020-In.-Thick TZM Molybdenum Alloy Sheet No. 74, Lot No. 13 Furnished by Universal-Cyclops Steel Corporation.

Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 13 Sheet 74 Guage 020

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.032	.42	.088	<.0035	.0018	<.001	.0042	.0003	.0001

Recrystallization:	End A	End B
As received D.P.H.	351	327
Fully Annealed D.P.H.	222	214
Rex. Temp. (°F)	2500	2450
% Recrystallized:	60	50
% Hardness Drop	78	67

Room Temp. Tensile	U.T.S. (KSI)	.2% Y.S.(KSI)	% Elong.
End A Transverse	142.1	135.6	7.9
End A Longitudinal	131.6	120.0	9.6
End B Transverse	140.3	131.8	6.6
End B Longitudinal	134.0	120.0	12.4

Notched Tensile:	End A	End B
Longit. Notch Strength:	141.9 KSI	139.9 KSI

2000°F Tensile:	U.T.S. (KSI)	Y.S. (KSI)	% Elong.
End A Transverse	81.4	80.3	3.8
End B Transverse	79.3	75.7	3.1

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-125°F	-125°F	-150°F
Next Failed Temp.	-150°F	-150°F	-175°F
Min. bend radius @ R.T.	OT	OT	OT
Springback angle	16°	20°	17°
Specimen size	1/2 x 2-1/2	Fixture Span length 1"	

Refractory Metal Sheet Evaluation

Material: TZM **Producer:** Universal-Cyclops Steel Corporation

Heat: KDTZM1196 **Lot:** 13 **Sheet:** 74 **Guage:** 020

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .300 thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .104 thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .025/.027 thick
Anneal 1 hr @ 2300°F belt grind and pickle to .020±.002 thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Table XII

Summary of Composition, Manufacturing Process, and Release Properties for 0.040-In.-Thick TZM Molybdenum Alloy Sheet No. 55, Lot No. 10 Furnished by Universal-Cyclops Steel Corporation.

Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 10 Sheet 55 Guage 040

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.030	.49	.104	<.001	<.0015	.002	.0012	.0003	.00017

Recrystallization:	End A	End B
As received D.P.H.	304	301
Fully Annealed D.P.H.	192	195
Rex. Temp. (°F)	2450	2500
% Recrystallized:	60	70
% Hardness Drop	74	83

Room Temp. Tensile	U.T.S.(KSI)	.2% Y.S. (KSI)	% Elong.
End A Transverse	130.1	124.8	8.9
End A Longitudinal	125.0	108.4	16.2
End B Transverse	131.2	124.6	12.0
End B Longitudinal	130.7	113.3	15.5

Notched Tensile:	End A	End B
Longit. Notch Strength:	133.1 KSI	135.1 KSI

2000°F Tensile:	U.T.S. (KSI)	Y.S.(KSI)	% Elong.
End A Transverse	80.4	75.2	5.0
End B Transverse	81.5	78.3	4.7

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-50°F	-100°F	-150°F
Next Failed Temp.	-75°F	-125°F	-175°F
Min. bend radius @ R.T.	0T	0T	0T
Springback angle	6°	6°	7°

Specimen size 1/2 x 2-1/2 Fixture Span length 1.25"

Refractory Metal Sheet Evaluation

Material: TZM Producer: Universal-Cyclops Steel Corporation

Heat: KDTZM1196 Lot: 10 Sheet: 55 Guage: 040

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .540 thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .187 thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .044/.048 thick
Anneal 1 hr @ 2300°F belt grind and pickle to .040±.003 thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Lxtensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Table XIII

Summary of Composition, Manufacturing Process, and Release Properties for 0.040-In.-Thick TZM Molybdenum Alloy Sheet No. 56, Lot No. 10 Furnished by Universal-Cyclops Steel Corporation.

Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 10 Sheet 56 Guage 040

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.031	.50	.119	<.0035	<.0015	<.001	.0015	.0002	.00024

Recrystallization:	End A	End B
As received D.P.H.	302	300
Fully Annealed D.P.H.	197	194
Rex. Temp. (°F)	2450	2450
% Recrystallized:	60	85
% Hardness Drop	68	89

Room Temp. Tensile	U.T.S. (KSI)	.2% Y.S. (KSI)	% Elong.
End A Transverse	138.6	131.7	7.3
End A Longitudinal	128.8	109.2	16.2
End B Transverse	132.4	124.2	11.5
End B Longitudinal	127.1	106.8	15.6

Notched Tensile:	End A	End B
Longit. Notch Strength:	139.4 KSI	132.0 KSI

2000°F Tensile:	U.T.S. (KSI)	Y.S. (KSI)	% Elong.
End A Transverse	84.9	79.8	6.2
End B Transverse	78.3	74.9	5.4

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-100°F	-150°F	-150°F
Next Failed Temp.	-125°F	-175°F	-175°F
Min. bend radius @ R.T.	0T	0T	0T
Springback angle	6°	9°	9°

Specimen size 1/2 x 2-1/2 Fixture Span length 1.25"

Refractory Metal Sheet Evaluation

Material: TZM **Producer:** Universal-Cyclops Steel Corporation

Heat: KDTZM1196 **Lot:** 10 **Sheet:** 56 **Guage:** 040

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .540 thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .187 thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .044/.048 thick
Anneal 1 hr @ 2300°F belt grind and pickle to .040 ±.003" thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Table XIV

Summary of Composition, Manufacturing Process, and Release Properties for 0.060-In.-Thick TZM Molybdenum Alloy Sheet No. 23, Lot No. 5 Furnished by Universal-Cyclops Steel Corporation.

Refractory Metal Sheet Evaluation

Material: TZM Producer: Universal-Cyclops Steel Corporation

Heat: KDTZM1196 Lot: 5 Sheet: 23 Guage: .060

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .760" thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .264" thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .063/.069" thick
Anneal 1 hr @ 2300°F belt grind and pickle to .060±.003" thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 5 Sheet 23 Guage .060

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.024	.50	.083	<.0035	<.0015	<.001	.0022	.0010	.0002

Recrystallization:	End A	End B
As received D.P.H.	304	318
Fully Annealed D.P.H.	198	208
Rex. Temp. (°F)	2450	2500
% Recrystallized:	60	50
% Hardness Drop	83	81

Room Temp. Tensile	U.T.S. (KSI)	.2% Y.S.(KSI)	% Elong.
End A Transverse	138.0	131.1	11.8
End A Longitudinal	128.6	113.1	15.1
End B Transverse	138.0	129.7	13.7
End B Longitudinal	132.4	106.1	17.4

Notched Tensile:	End A	End B
Longit. Notch Strength:	138.3 KSI	135.0 KSI

2000°F Tensile:	U.T.S.(KSI)	Y.S.(KSI)	% Elong.
End A Transverse	82.0	79.5	6.4
End B Transverse	87.2	84.7	5.9

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-50°F	-50°F	-50°F
Next Failed Temp.	-75°F	-75°F	-75°F
Min. bend radius @ R.T.	OT	OT	OT
Springback angle	<5°	> <5°	<5°

Specimen size 3/4 x 3-1/4 Fixture Span length 1-1/2"

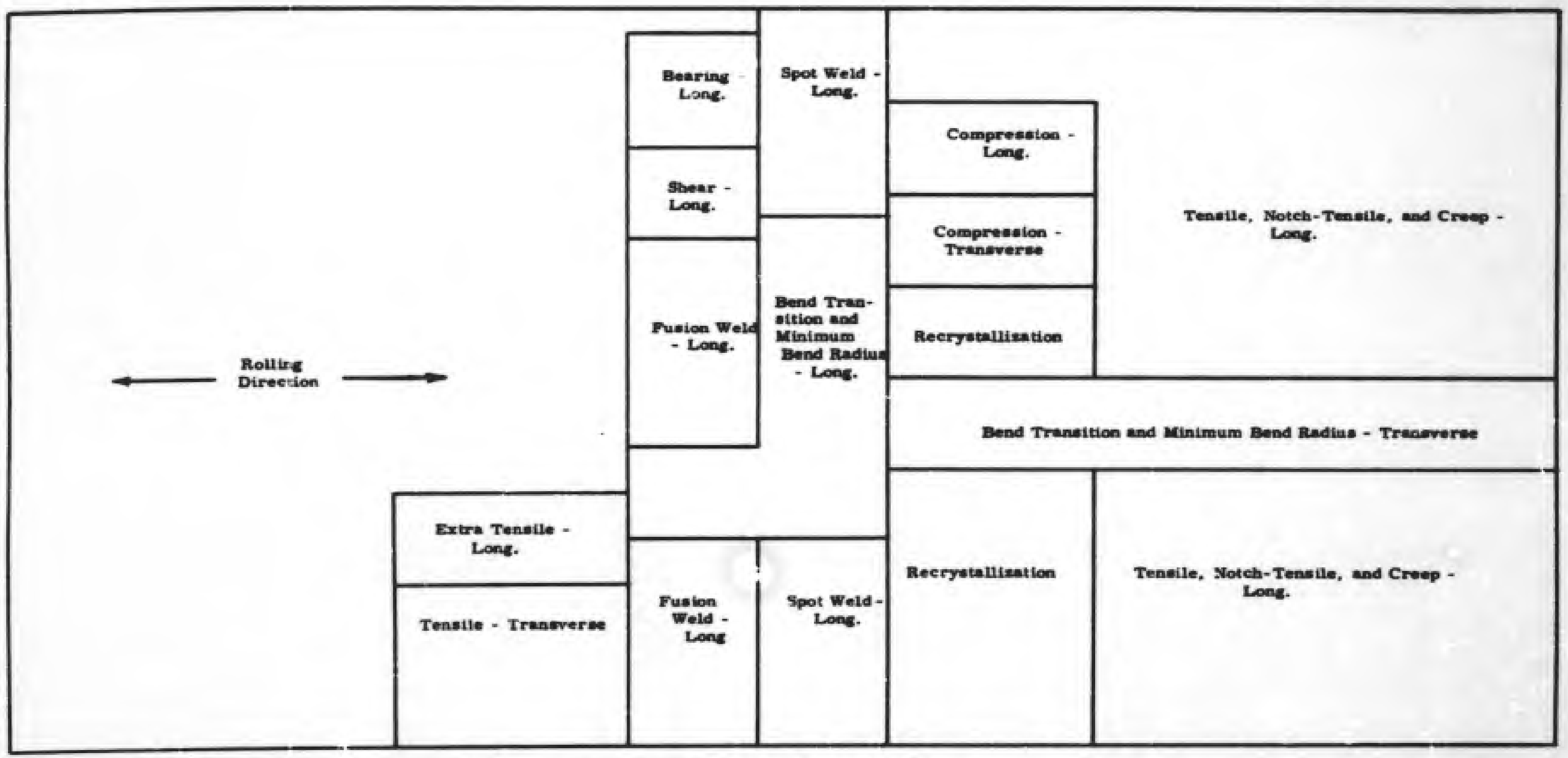


Figure 1. The location of specimens from 0.040-in-thick TZM sheet No's. 55 and 56, Lot No. 10.

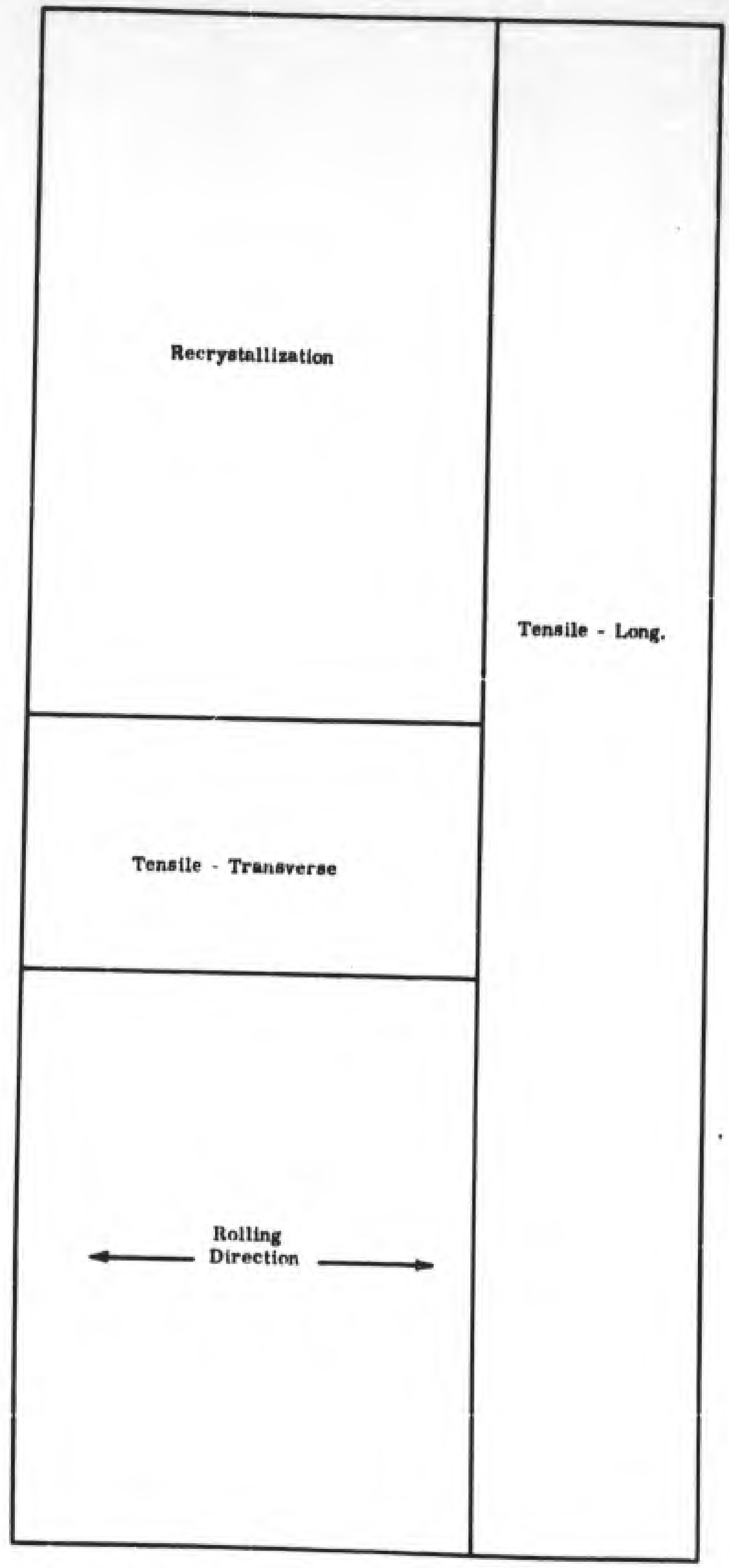


Figure 2. The location of specimen from the 0.020-in.-thick TZM sheet No. 74, Lot No. 13 and the 0.060-in.-thick TZM sheet No. 23, Lot No. 5.

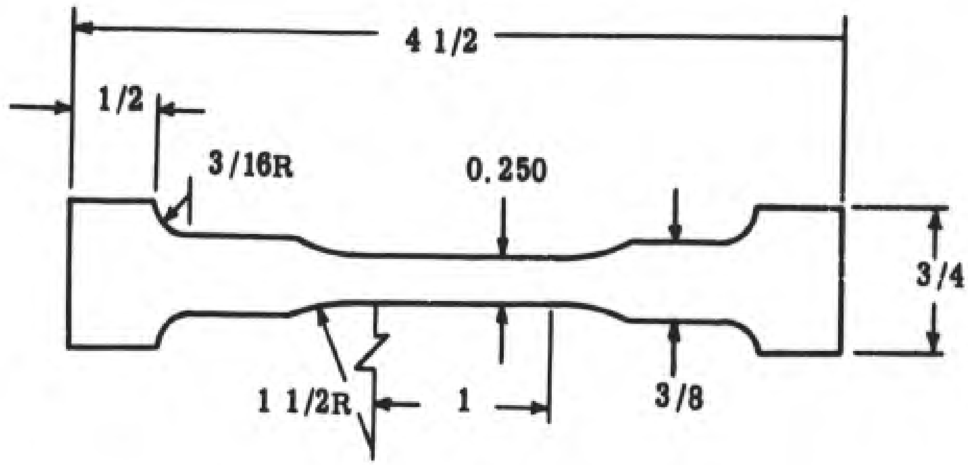


Figure 3. Specimen for room-temperature tensile evaluation of tungsten sheet.

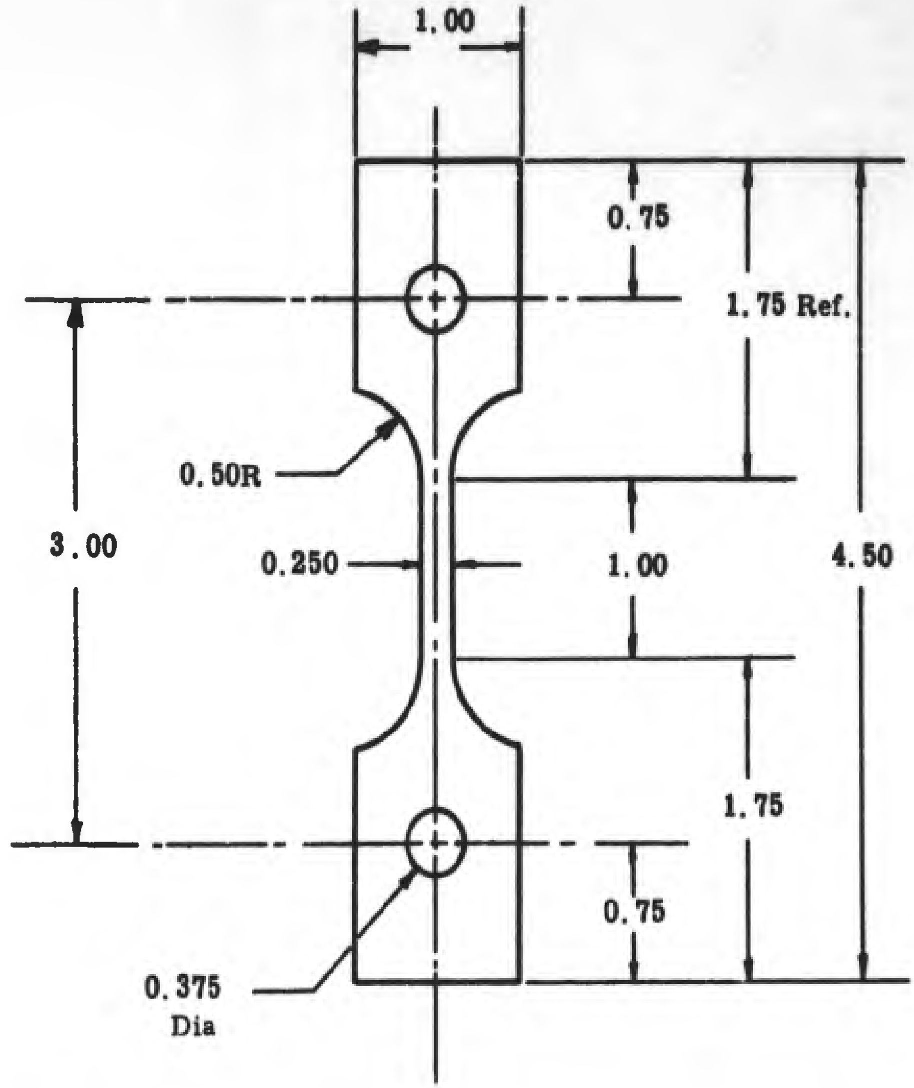
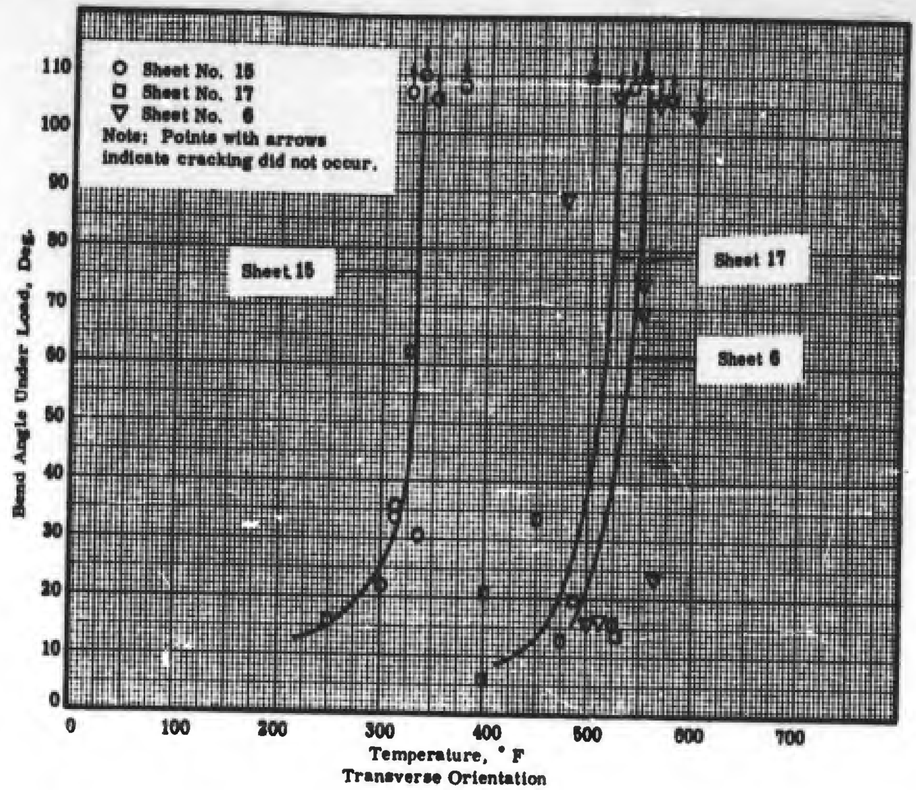


Figure 4. Specimen for elevated-temperature tensile evaluations of tungsten sheet.



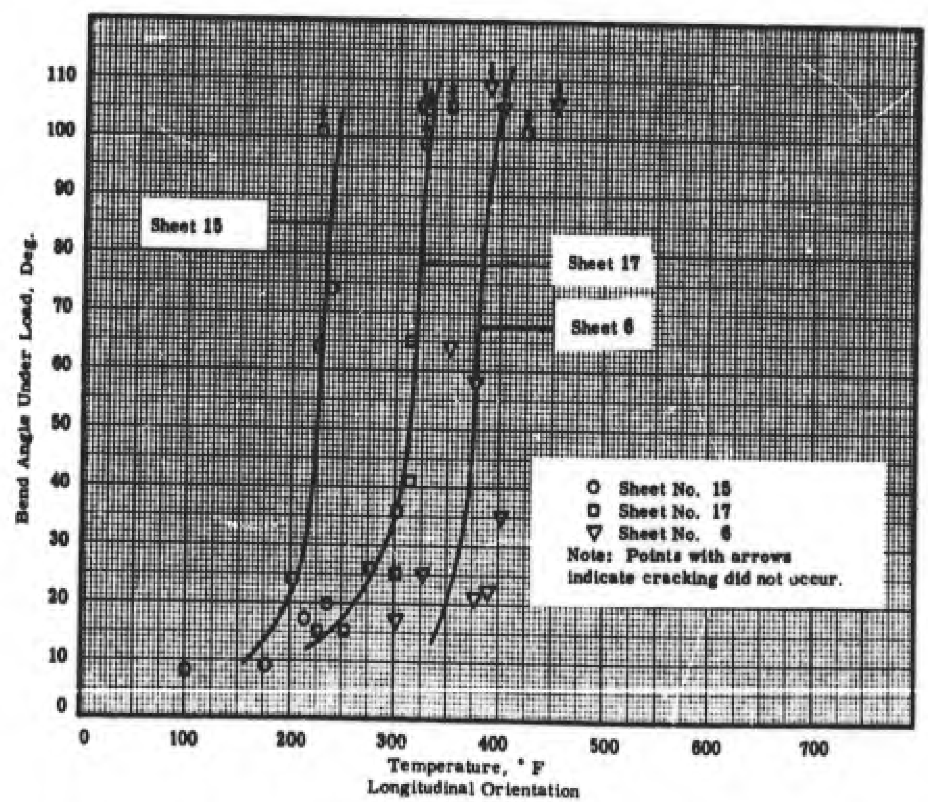
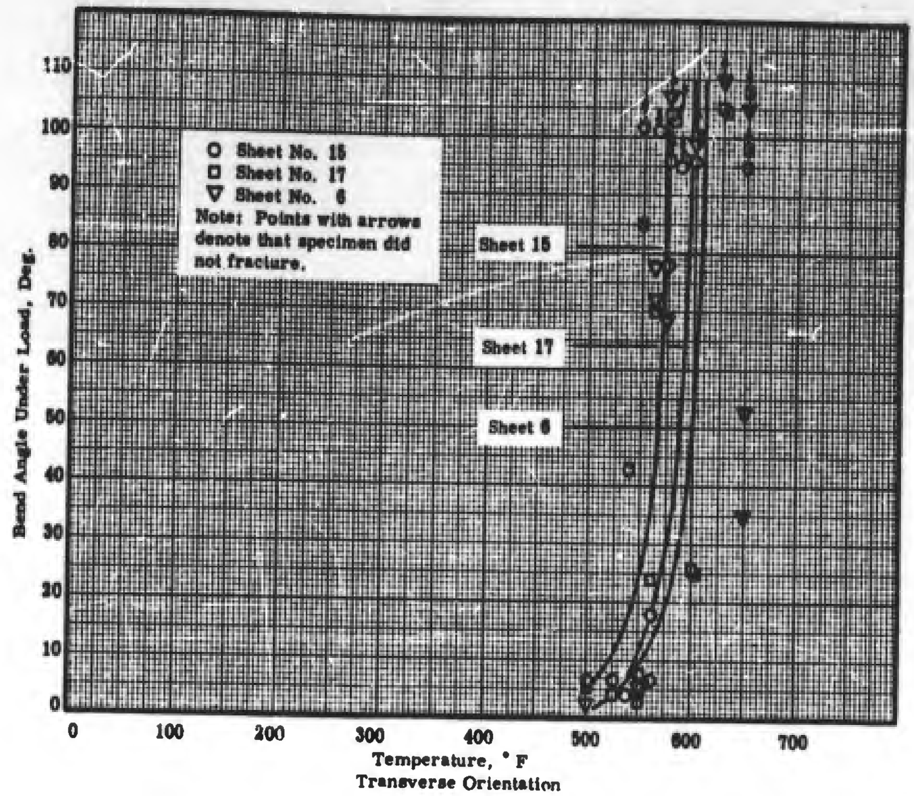


Figure 5. Bend-transition-temperature curves based on bend angle under load for the longitudinal and transverse orientation of three 0.060-in.-thick tungsten sheets in the optimum condition using a punch with a radius of 4t, a span of 1.5 in., and a ram rate of 1.0 in./in./min.



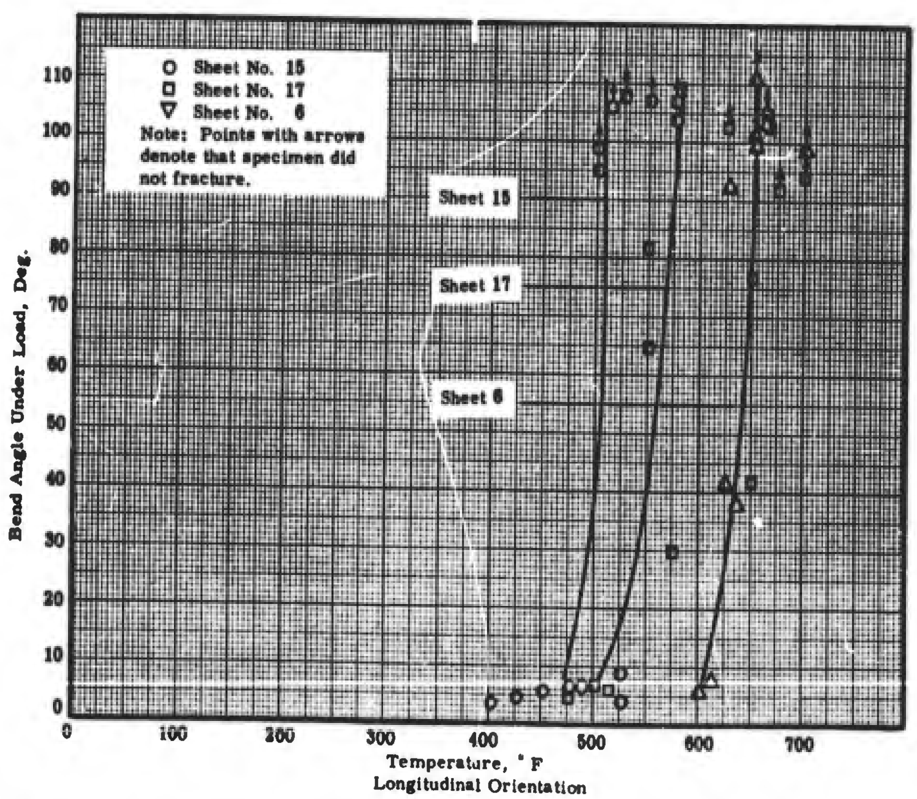


Figure 6. Bend-transition-temperature curves based on bend angle under load for the longitudinal and transverse orientation of three 0.060-in.-thick tungsten sheets in the recrystallized condition using a punch with a radius of 4t, a span of 1.5 in., and a ram rate of 1.0 in./in./min.

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