I

Report No. BMI-1143
Metallurgy and Ceramics
(TID-4500, 12th Ed.)

Contract No. W-7405-eng-92

INVESTIGATION OF SOME NIOBIUM-BASE ALLOYS

by

Stan J. Paprocki
John T. Stacy

October 31, 1956

BATTELLE MEMORIAL INSTITUTE
505 King Avenue
Columbus 1, Ohio

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
INTRODUCTION	1
EXPERIMENTAL WORK	2
Alloy Preparation	2
Metallographic Examination	3
Hardness Results	5
Oxidation Results	12
CONCLUSIONS	15
REFERENCES	16

INVESTIGATION OF SOME NIOBIUM-BASE ALLOYS

Stan J. Paprocki and John T. Stacy

Twenty-seven niobium-base alloys, containing 5 w/o of aluminum, chromium, iron, molybdenum, nickel, tantalum, tungsten, vanadium, or zirconium, and with an addition of 0, 9.5, or 19.0 w/o titanium, were examined for workability, ductility, hardness at room temperature and 1600 F, and oxidation resistance at 1800 F.

Addition of titanium generally improved workability, increased hot hardness, and promoted oxidation resistance. Some exceptions to this pattern were noted: the hardest alloy at 1600 F, niobium-5 w/o zirconium, softened with added titanium, and the oxidation resistance of the niobium-5 w/o molybdenum and the niobium-5 w/o vanadium alloys was not increased by additions of titanium.

INTRODUCTION

Several factors combine to make niobium or niobium-base alloys attractive materials for high-temperature structural use. These include high melting temperatures, good elevated-temperature strengths, medium densities, and formation of stable oxides. Unfortunately, niobium must be protected from oxidation when used in high-temperature air. Also, it is relatively high-cost material. These latter two disadvantages present a challenge to present-day technology.

Although the room-temperature tensile strength of niobium is not exceptional, varying from 50,000 to 100,000 psi, its loss of strength with increasing temperature is so gradual that at high temperatures it becomes attractive strengthwise for structural use. In this regard, it can be compared with molybdenum. It is apparently somewhat inferior in strength to molybdenum at high temperatures, but possesses a lower density than does molybdenum (8.57 versus 10.2 g per cm³) and forms a relatively stable oxide. Also, for nuclear-reactor use, niobium has a decided advantage over molybdenum because of its lower absorption cross section for thermal neutrons.

In previous work by the authors and their associates, the addition of titanium to niobium was found to improve the workability of arc-melted niobium ingots, increase the short-time rupture strength of niobium at 2200 F in helium⁽¹⁾, and improve the oxidation resistance of niobium at

(1) References listed at end.

1800 F in air⁽²⁾. However, creep-rupture tests at 1800 F in vacuum indicated that the 100-hr rupture strength of niobium was lowered from 14,500-16,500 psi to 12,500 psi by the addition of 10 w/o titanium⁽¹⁾, the optimum titanium addition for strengthening as determined by short-time rupture tests at 2200 F in helium.

With the above-mentioned advantages of titanium additions in mind, the present investigation was undertaken to examine other niobium-base alloys, with and without titanium. Hardness tests at 1600 F were selected as the basis for judging relative high-temperature strengths, although it was recognized that at best these tests would only provide a very rough guide for future high-temperature-alloy studies. Other properties of interest for investigation included workability, microstructure, ductility, and oxidation resistance. With the exception of titanium, the alloying elements were selected on the basis of known alloying characteristics or thermal-neutron-absorption cross sections. The selected alloying elements in increasing order of thermal-neutron-absorption cross sections per unit of weight were: (1) zirconium, (2) aluminum, (3) molybdenum, (4) iron, (5) chromium, (6) nickel, (7) vanadium, (8) tungsten, and (9) tantalum.

EXPERIMENTAL WORK

Twenty-seven niobium-base alloys were selected for the survey. Each alloy contained 5 w/o of one of the nine alloying elements and 0, 9.5, or 19.0 w/o titanium as the ternary addition. Workability was checked by cold forging and cold rolling. Room-temperature hardnesses were taken of the cast, forged, and cold-rolled alloys to determine work-hardening characteristics. Also, the hardness of each alloy was taken at 1600 F in vacuum in order to estimate the relative high-temperature strength of the alloy. The as-cast microstructure of each alloy was examined for second phase, and bend ductility was obtained on cold-rolled strips of each alloy. To estimate the relative oxidation resistance of the alloys, weight-gain data were determined for each alloy after exposure at 1800 F in still air.

Alloy Preparation

The niobium-base alloys were prepared by melting finely divided and well-mixed charge materials four times in a tungsten-electrode arc furnace. Prior to melting, the furnace chamber was successively evacuated and filled with AEC-grade helium three times, the final furnace-chamber atmosphere being gettered before alloying by arc-melting a small charge of zirconium. Each alloy weighed approximately 25 g. The charge materials were of commercial purity. Fansteel niobium sheet, which had a hardness of about 135 DPHN, was used as the base material. The other charge metals were:

<u>Alloying Element</u>	<u>Description</u>	<u>Supplier</u>
Aluminum	2S sheet	Aluminum Company of America
Chromium	Electrolytic	Union Carbide and Carbon Corporation
Iron	Punchings	American Rolling Mill Company
Molybdenum	Sheet	Fansteel Metallurgical Corporation
Nickel	Sheet	International Nickel Company
Tantalum	Sheet	Fansteel Metallurgical Corporation
Titanium	Crystal bar	Foote Mineral Company
Tungsten	Rod	Fansteel Metallurgical Corporation
Vanadium	Ductile chips	Union Carbide and Carbon Corporation
Zirconium	Crystal bar	Foote Mineral Company

After casting, the arc-melted alloy buttons were machined top and bottom to secure smooth, parallel surfaces for subsequent cold working. The initial deformation consisted in press forging each button at room temperature to a 50 per cent reduction in thickness in one stroke. The results of this operation are listed in Table 1. It will be noted from these data that, with the possible exception of those alloys containing 5 w/o iron, the cold forgeability of all of the binary alloys was generally improved by the addition of titanium.

The press-forged buttons were cold rolled without intermediate annealing to a total cold reduction of 95 per cent (including the press forging): Rolling reductions were 25 per cent on the first pass, 15 per cent on the second, and 10 per cent on each succeeding pass. Qualitative results of the cold-rolling operation and bend ductility of the resultant alloy strips are given in Table 1. Again, it will be noted that the quality of the rolled alloys as well as their ductility was improved by additions of titanium to the niobium-base binary alloy.

Metallographic Examination

All of the as-cast alloys were examined for microstructure. Alloy 1, niobium-5 w/o zirconium, contained considerable second phase. With additions of titanium, the amount of second phase decreased. This effect will be noted in the typical cast structures of Alloy 1 and of Alloy 3, the niobium-5 w/o zirconium alloy and the niobium-19 w/o titanium-5 w/o zirconium alloy, respectively, which are shown in Figures 1 and 2. The niobium-5 w/o aluminum, Alloy 4, showed a scattering of many small spheroidal particles. These were not observed in Alloys 5 and 6, which contained titanium in addition to 5 w/o aluminum. This scattering of small particles was noted in several of the other binary alloys and may have been related to gas or carbon content, the solubility of which was increased by additions of titanium to the niobium binary alloy.

TABLE 1. COMPOSITIONS OF ALLOYS AND RESULTS OF FORGING AND ROLLING

Alloy	Nominal Composition, w/o			Press-Forging Results ^(a)	Rolling Results
	Niobium	Titanium	Other		
1	95.0	0.0	5Zr	Some edge cracking	Fair, cracks, ductile
2	85.5	9.5	5Zr	No cracking	Excellent, very ductile
3	76.0	19.0	5Zr	No cracking	Excellent, very ductile
4	95.0	0.0	5Al	Little cracking	Fair, some tears, fairly ductile
5	85.5	9.5	5Al	Some cracking	Good, ductile
6	76.0	19.0	5Al	No cracking	Excellent, very ductile
7	95.0	0.0	5Mo	Some cracking	Good, some tears, ductile
8	85.5	9.5	5Mo	Severe cracking	Good, some tears, ductile
9	76.0	19.0	5Mo	No cracking	Excellent, very ductile
10	95.0	0.0	5Fe	Some edge cracking	No good, broke up, very brittle
11	85.5	9.5	5Fe	Severe edge cracking	Poor, tears, brittle
12	76.0	19.0	5Fe	Some edge cracking	Good, some cracks, fairly ductile
13	95.0	0.0	5Cr	No cracking	Very good, slight edge cracks, ductile
14	85.5	9.5	5Cr	Severe edge cracking	Poor, severely cracked, tears, ductile
15	76.0	19.0	5Cr	No cracking	Excellent, very ductile
16	95.0	0.0	5Ni	Severe edge cracking	Fair, tears, breaks on bending
17	85.5	9.5	5Ni	Slight edge cracking	Fair, tears, breaks on bending
18	76.0	19.0	5Ni	No cracking	Good, some tears, breaks on bending
19	95.0	0.0	5V	Slight edge cracking	Fair, tears, some ductility
20	85.5	9.5	5V	No cracking	Excellent, ductile
21	76.0	19.0	5V	No cracking	Excellent, ductile
22	95.0	0.0	5W	No cracking	Very good, slight tears, very ductile
23	85.5	9.5	5W	No cracking	Excellent, very ductile
24	76.0	19.0	5W	No cracking	Excellent, very ductile
25	95.0	0.0	5Ta	No cracking	Excellent, very ductile
26	85.5	9.5	5Ta	No cracking	Excellent, very ductile
27	76.0	19.0	5Ta	No cracking	Excellent, very ductile

(a) All specimens press forged well, with some variations in cracking as noted.

The iron series, Alloys 10, 11, and 12, and the nickel series, Alloys 16, 17, and 18, showed second phases. Photomicrographs of the niobium-5 w/o iron and the niobium-5 nickel alloys are shown in Figures 3 and 4. Both of these systems contain low-melting eutectics⁽³⁾.

Binary alloys containing 5 w/o each of chromium, molybdenum, tantalum, tungsten, and vanadium, as well as the 5 w/o aluminum alloy exhibited complete solid-solution-type structures. These observations correspond to published equilibrium-diagram data for the niobium-chromium⁽⁴⁾ and the niobium-vanadium⁽⁵⁾ systems, but not for the niobium-zirconium⁽⁶⁾ system, in which second phase was observed at the 5 w/o zirconium level. In regard to the latter, Rogers and Atkins reported that transformation in niobium-rich niobium-zirconium alloys was sluggish and, in the present instance, equilibrium conditions certainly were not established. However, Rogers and Atkins did not explore the niobium-rich end of the diagram extensively, and some error in their published equilibrium diagrams may be possible in this region. In regard to the other alloying elements, titanium is known to have wide range of solubility in niobium⁽⁷⁾, and molybdenum, tantalum, and tungsten are reported to form complete series of solid solutions with niobium⁽⁸⁾.

Hardness Results

Vickers hardness numbers were determined at room temperature for the alloys as cast, as cold forged to a 50 per cent reduction in area, and as forged and cold rolled to a 95 per cent reduction in area. Similar data were obtained at 1600 F in vacuum for the forged material. The loads used on the pyramid indenter were 10 kg for the as-cast and as-forged material at room temperature, 1 kg for the as-forged and rolled material at room temperature, and 0.870 kg for the as-forged alloys at 1600 F. The respective data were obtained with an Amsler tester, a Tukon tester, and a tester especially constructed for obtaining hot-hardness values in vacuum. This latter apparatus has been described elsewhere⁽⁹⁾. In regard to the hardness data obtained, it should be recognized that, while the diamond pyramid hardness number is theoretically independent of the load employed, some variations in this relationship have been noted. Thus, a comparison of hardnesses among data obtained using different loads may not be fully justified.

Hardness data for all alloys are listed in Table 2. Maximum, minimum, and average hardness numbers are given. From six to ten readings per specimen were taken at room temperature, while either four or five readings per specimen were taken at 1600 F. The average hardness numbers have been plotted in Figures 5 through 13. A summary plot of the hardnesses of the alloys at 1600 F versus their composition is presented in Figure 14. Previous work has shown that the 1600 F hardness of niobium-0 to 20 w/o titanium alloys reaches a peak value at about 10 w/o titanium⁽¹⁾. It will be noted in Figure 14 that, with the exception of those

500X

N33831

Etch: 1HF-5HNO₃-10H₂O

FIGURE 1. ALLOY 1 (95 w/o NIOBIUM-5 w/o ZIRCONIUM) AS CAST

500X

N33832

Etch 1HF-5HNO₃-10H₂O

FIGURE 2. ALLOY 3 (76 w/o NIOBIUM-19 w/o TITANIUM-5 w/o ZIRCONIUM) AS CAST

500X

N33833

Etch. 1HF-5HNO₃-10H₂O

FIGURE 3. ALLOY 10 (95 w/o NIOBIUM-5 w/o IRON) AS CAST

500X

N33834

Etch: 1HF-5HNO₃-10H₂O

FIGURE 4. ALLOY 16 (95 w/o NIOBIUM-5 w/o NICKEL) AS CAST

TABLE 2. SUMMARY OF HARDNESS TESTS

Alloy	Nominal Composition (Balance Niobium), w/o		Room-Temperature Hardness, DPHN									1600 F Hardness, DPHN, as Forged		
	Titanium	Other	As Cast			As Forged			As Rolled			Max	Min	Avg
			Max	Min	Avg	Max	Min	Avg	Max	Min	Avg			
1	0	5Zr	249	210	225	310	232	257	257	210	234	297	239	270
2	9.5	5Zr	249	223	232	277	244	262	290	251	263	286	159	220
3	19.0	5Zr	239	212	225	260	239	249	251	205	234	250	183	218
4	0	5Al	214	193	203	268	223	236	368	224	313	183	168	175
5	9.5	5Al	283	232	265	412	280	332	321	269	313	225	205	214
6	19.0	5Al	321	296	310	362	321	341	348	297	330	142	129	137
7	0	5Mo	234	219	227	260	223	249	283	197	245	132	118	124
8	9.5	5Mo	229	210	216	286	251	274	290	224	269	215	178	202
9	19.0	5Mo	254	221	244	306	262	277	290	251	276	163	158	160
10	0	5Fe	286	265	277	349	299	332	378	313	358	245	171	224
11	9.5	5Fe	332	262	317	362	229	313	413	321	390	175	144	163
12	19.0	5Fe	332	296	317	362	299	332	378	339	368	95	91	93
13	0	5Cr	225	192	206	260	223	246	269	201	239	138	120	127
14	9.5	5Cr	232	203	216	336	239	286	330	269	305	231	214	222
15	19.0	5Cr	257	229	246	296	254	274	313	263	290	139	104	124
16	0	5Ni	251	227	239	317	283	299	390	297	368	96	95	96
17	9.5	5Ni	325	296	313	371	303	336	390	313	358	117	83	98
18	19.0	5Ni	303	257	280	303	249	274	348	257	290	179	154	164
19	0	5V	262	227	244	280	260	271	378	305	339	57	43	49
20	9.5	5V	265	216	236	277	241	257	297	251	276	168	144	158
21	19.0	5V	236	214	227	254	234	244	276	229	257	161	132	142
22	0	5W	216	201	210	232	204	221	234	205	219	139	123	131
23	9.5	5W	229	219	225	257	216	232	276	214	245	172	134	155
24	19.0	5W	221	210	214	227	210	221	263	224	234	143	120	131
25	0	5Ta	199	185	188	249	197	216	239	193	214	149	130	142
26	9.5	5Ta	210	201	203	249	210	223	257	193	239	194	171	182
27	19.0	5Ta	201	192	197	236	227	229	263	219	251	120	108	114

FIGURE 5. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o ZIRCONIUM BINARY AND TERNARY ALLOYS

FIGURE 6. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o ALUMINUM BINARY AND TERNARY ALLOYS

FIGURE 7. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o MOLYBDENUM BINARY AND TERNARY ALLOYS

FIGURE 8. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o IRON BINARY AND TERNARY ALLOYS

FIGURE 9. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o CHROMIUM BINARY AND TERNARY ALLOYS

FIGURE 10. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o NICKEL BINARY AND TERNARY ALLOYS

FIGURE 11. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o VANADIUM BINARY AND TERNARY ALLOYS

FIGURE 12. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o TUNGSTEN BINARY AND TERNARY ALLOYS

FIGURE 13. HARDNESS VERSUS COMPOSITION OF NIOBIUM-5 w/o TANTALUM BINARY AND TERNARY ALLOYS

FIGURE 14. HOT HARDNESS VERSUS COMPOSITION OF NIOBIUM-BASE BINARY AND TERNARY ALLOYS AT 1600 F

alloys containing 5 w/o zirconium, 5 w/o iron, and 5 w/o nickel, this trend was followed with increasing titanium in the ternary alloys. It is probably significant that these three elements, zirconium, iron, and nickel, formed second phases with niobium at the 5 w/o level, while the others formed only solid solutions.

The niobium-5 w/o zirconium alloy exhibited the highest hardness at 1600 F of any of the alloys tested. With added titanium, the hardness fell off rapidly and, concurrently, the second phase observed in the binary alloy disappeared (see Figures 1 and 2). It will be noted in Figure 5 that the hardness of this alloy was apparently greater at 1600 F than it was at room temperature. To check the accuracy of these data, a series of niobium-zirconium alloys was tested for hardness at room temperature and at 1600 F. The results are shown below:

<u>Nominal Composition, w/o</u>		<u>Hardness^(a), DPHN</u>	
<u>Niobium</u>	<u>Zirconium</u>	<u>Room Temperature</u>	<u>1600 F</u>
98	2	164	229
95	5	206	324
90	10	232	251
85	15	274	298

(a) Average of 5 readings.

On the basis of the hardness values obtained for the niobium-zirconium alloy series, it was concluded that the niobium-zirconium alloys are definitely harder at 1600 F than at room temperature, especially at the 2 and 5 w/o zirconium levels. Metallographic examination of these four alloys showed that all of them contained second phase at room temperature. It appears probable that the greater hardness of these alloys at 1600 F may be ascribed to solution of the second phase and resultant hardening of the matrix.

Oxidation Results

To determine the effect of alloying on the oxidation characteristics of niobium, small specimens of each alloy were checked for short-time oxidation resistance by the weight-gain method. The alloy specimens, machined to about 0.5 by 0.5 by 0.07 in., were ground on 400-grit emery paper, measured, washed in acetone, rinsed in absolute alcohol, and weighed. For testing, each specimen was exposed in a prefired porcelain crucible, each crucible having been weighed, exposed for 1 hr at 1800 F, and reweighed just prior to the oxidation test. The crucibles containing the specimens were then exposed for 1 hr at 1800 F in still air. After exposure, the crucibles, specimens, and collected oxide were reweighed and the weight gained during exposure was calculated as grams per square inch

TABLE 3. SUMMARY OF OXIDATION-TEST RESULTS

Specimens Exposed for 1 Hr at 1800 F in Air

Alloy	Nominal Composition, w/o			Weight Gain, g/in. ²	Nature of Oxide		
	Niobium	Titanium	Other		Color	Tenacity	Texture
First Group							
Std	100	—	—	0.3416	White	Fair	Smooth
1	95	0	5Zr	0.6897	White	Fair	Smooth
2	85.5	9.5	5Zr	0.1642	White	Good	Glazed
3	76	19	5Zr	0.0706	White-yellow	Good	Glazed
4	95	0	5Al	0.3289	White	Fair	Smooth
5	85.5	9.5	5Al	0.0805	White	Good	Glazed
6	76	19	5Al	0.0983	White-yellow	Good	Glazed
7	95	0	5Mo	0.0528	Gray	Poor	Coarse, powdery
8	85.5	9.5	5Mo	0.0547	Gray	Fair	Coarse, powdery
9	76	19	5Mo	0.0527	Gray	Good	Coarse
Second Group							
Std	100	—	—	0.2883	White	Fair	Smooth
10	95	0	5Fe	0.2335	Light green	Fair	Smooth
11	85.5	9.5	5Fe	0.0501	Brown-gray	Poor	Smooth, flaked
12	76	19	5Fe	0.0437	Brown-light green	Fair	Smooth, flaked
13	95	0	5Cr	0.2352	Light green	Good	Smooth
14	85.5	9.5	5Cr	0.0323	Light green	Very good	Smooth, flaked
15	76	19	5Cr	0.0315	Tan	Good	Powdery
16	95	0	5Ni	0.3379	Tan-brown	Fair	Smooth
17	85.5	9.5	5Ni	0.1033	Light green	Poor	Fairly smooth
18	76	19	5Ni	0.0803	Violet	Very good	Smooth, flaked
Third Group							
Std	100	—	—	0.3356	White	Fair	Smooth
19	95	0	5V	0.0526	Light green	Fair	Smooth, flaked
20	85.5	9.5	5V	0.0432	Violet	Very good	Smooth, powdery
21	76	19	5V	0.0913	Violet	Very good	Powdery
22	95	0	5W	0.4362	White	Fair	Smooth
23	85.5	9.5	5W	0.0542	White	Very good	Smooth, flaked
24	76	19	5W	0.0775	Yellow-white	Poor	Glazed
25	95	0	5Ta	0.3683	White	Fair	Smooth
26	85.5	9.5	5Ta	0.0528	White	Fair	Smooth, flaked
27	76	19	5Ta	0.0470	White-light green	Poor	Smooth, flaked

FIGURE 15. WEIGHT GAIN VERSUS COMPOSITION OF NIOBIUM-BASE BINARY AND TERNARY ALLOYS EXPOSED FOR 1 HR AT 1800 F IN AIR

of original specimen area. A niobium standard was exposed with each group of specimens. Some estimate of the accuracy of the tests may be obtained by noting that the three pure-niobium specimens varied within ± 0.0267 g per in.² of the mean weight gain, or ± 8.5 per cent. Weight-gain data are presented in Table 3 along with observations regarding the nature of the oxide formed.

For clarity, the data presented in Table 3 have been plotted in Figure 15. In general, the oxidation resistance of the niobium binary alloys was improved with additions of titanium, the optimum titanium addition being of the order of 10 to 15 w/o. Two exceptions to this generality were noted in the niobium-5 w/o molybdenum and the niobium-5 w/o vanadium alloys, where additions of titanium did not improve the oxidation resistance of the binary alloys.

CONCLUSIONS

A number of conclusions may be drawn from the experiments performed on the 27 niobium-base alloys containing 5 w/o of aluminum, chromium, iron, molybdenum, nickel, tantalum, tungsten, vanadium, or zirconium, with or without titanium additions. Based on this work, it is concluded that:

- (1) The workability of these alloys is improved by additions of titanium, the best workability occurring in those alloys having solid-solution structures.
- (2) At room temperature, alloys containing aluminum, iron, or nickel are the hardest. Although they work harden more rapidly than pure niobium, some of the alloys harden at a particularly high rate. Those alloys containing aluminum, iron, nickel, or vanadium work harden to the greatest extent; ternary additions of titanium lower the work-hardening effect.
- (3) At 1600 F, the niobium-5 w/o zirconium alloy is the hardest, being harder at 1600 F than at room temperature. Additions of titanium increase the 1600 F hardness of most of these alloys to a maximum at about 10 w/o titanium, although iron, nickel, and zirconium alloys do not follow this pattern.
- (4) At 1800 F, maximum oxidation resistance is secured with additions of chromium and titanium to niobium. With the exception of those alloys containing molybdenum and vanadium, the addition of titanium improved oxidation resistance at 1800 F.

REFERENCES

- (1) Saller, H. A., Stacy, J. T., and Porembha, S. W., "Initial Investigation of Niobium-Base Alloys", BMI-1003, 21 (May, 1955).
- (2) Battelle Memorial Institute, unpublished data.
- (3) Metals Handbook, American Society for Metals, 1186-1187 (1948).
- (4) Elintin, V. P., and Funke, V. F., "Some Data on the Equilibrium Diagram of the Chromium-Niobium System", Academy of Sciences of the U.S.S.R., 3, 68-76 (1956).
- (5) Wilhelm, H. A., Carlson, O. N., and Dickinson, J. M., "Columbium-Vanadium Alloy System", Trans. AIME, 200, 915-918 (1954).
- (6) Rogers, B. A., and Atkins, D. F., "Zirconium-Columbium Diagram", Trans. AIME, 203, 1034-1040 (1955).
- (7) Hansen, M., Kamen, E. L., Kessler, H. D., and McPherson, D. J., "Systems Titanium-Molybdenum and Titanium-Columbium", Trans. AIME, 191, 886 (1951).
- (8) Myers, R. H., "The Constitution and Properties of Alloys Containing Tantalum and Columbium", Metallurgia, 39, 57-63 (December, 1948).
- (9) Chubb, W., "Contribution of Crystal Structure to the Hardness of Metals", Trans. AIME, 203, 189-192 (1955).

SJP/JTS:bjz:sjk