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TENSILE AND CREEP PROPERTIES OF TITANIUM-VANADIUM, TITANIUM-MOLYBDENUM, AND TITANIUM-NIOBIUM ALLOYS

Hugh R. Gray

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

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TENSILE AND CREEP PROPERTIES OF TITANIUM-VANADIUM, TITANIUM-MOLYBDENUM, AND TITANIUM-NIOBIUM ALLOYS

by Hugh R. Gray

Lewis Research Center

SUMMARY

Tensile and creep properties of five series of experimental beta-phase titanium alloys were determined. The alloy series were titanium-niobium, titanium-molybdenum, titanium-vanadium-silicon, titanium-vanadium-aluminum, and titanium-vanadium-aluminum-silicon. Alloys were tested in the as-rolled condition, with the exception of a few compositions that were tested in the as-cast condition because they cracked during rolling. Alloys were tensile tested at 23°, 500°, and 650° C. Alloys were creep tested for 100 hours at 500° and 650° C. Post-creep tensile tests were conducted at 23° C to determine residual tensile properties of the alloys.

Titanium-vanadium alloys had substantially greater tensile and creep strength than any of the titanium-niobium and titanium-molybdenum alloys tested. The specific tensile strengths of Ti-50V-(3 to 5)Al-(1 to 2)Si alloys were equivalent to those of commercial titanium alloys at 23° C and superior to those of commercial titanium alloys in the temperature range 500° to 650° C.

The Ti-50V-3Al-1Si alloy had the best balance of tensile strength, creep strength, and metallurgical stability. The creep strength of this alloy was far superior to that of a commonly used commercial titanium alloy, Ti-6Al-4V, at 500° C. Its creep strength was almost equivalent to that of two newly developed commercial titanium alloys, Ti-5621S and Ti-11.

INTRODUCTION

All titanium alloys currently used for high-temperature applications are alpha-beta types, sometimes termed near-alpha or super-alpha titanium alloys. Most of these alloys have an aluminum content in the range 5 to 8 weight percent, which increases the alpha-to-beta transformation temperature. The retardation of the allotropic transformation, alpha to beta, is the principal reason for the high-temperature strength capability of this type of titanium alloy. This approach of stabilizing the alpha phase of titanium alloys to higher temperatures is analogous to suppressing the austenitic phase of stainless steels by alloying with chromium so that they remain ferritic from room temperature to their melting point.

The other way of preventing the allotropic transformation in titanium alloys, stabilizing the beta phase, has not been extensively studied. This approach is analogous to stabilizing the austenitic phase of nickel-chromium stainless steels so that they remain austenitic from room temperature to essentially their melting point.

There are a few commercially available titanium alloys which are termed beta alloys, but in fact they are only partially stabilized or are metastable. Therefore, they are not useful alloys for elevated-temperature applications. A few exploratory investigations concerned with stable beta-phase titanium alloys have been reported in the literature: titanium-vanadium (refs. 1 to 4), titanium-molybdenum (refs. 3 to 6), and titanium-niobium (ref. 7). In particular, titanium-vanadium-aluminum and titanium-vanadium-silicon alloys have been shown to have excellent tensile and rupture strength to about 500° C (ref. 1).

This exploratory investigation was conducted to determine the potential of beta-titanium alloys for turbine engine compressor components or other structural applications to temperatures of approximately 650° C. Limited tensile and creep data were determined for a variety of binary, ternary, and quaternary titanium-base alloys. Concentration levels of vanadium, molybdenum, and niobium were selected to stabilize the beta phase to room temperature. These basic alloys were modified with potential solid solution and precipitation strengthening elements, aluminum and silicon. Alloys were tested in the as-rolled condition, with the exception of a few compositions that were tested in the as-cast condition because they cracked during rolling. Alloys were tensile tested at 23°, 500°, and 650° C. Alloys were creep tested at 500° and 650° C for 100 hours. Post-creep tensile tests were conducted at 23° C to determine residual tensile properties of the alloys.

MATERIALS, SPECIMENS, AND PROCEDURE

Materials

A total of 42 alloys were investigated Their nominal compositions, in weight percent, and nominal densities are listed in table I. Measured densities were within 1 percent of nominal values. For convenience, the alloys are separated into five groups: titanium-niobium (Ti-Nb) series, titanium-molybdenum (Ti-Mo) series, titanium-vanadium-silicon (Ti-V-Si) series, titanium-vanadium-aluminum (Ti-V-Al) series, and titanium-vanadium-aluminum-silicon (Ti-V-Al-Si) series.

The alloys were melted by Titanium Metals Corporation of America in a plasma arc furnace under 1 atmosphere of argon. Heats of about 500 grams were cast into two buttons approximately 2 centimeters by 4 centimeters by 10 centimeters. Buttons were rough rolled from 1100° C to 2-centimeter-square bar and final rolled from 930° C to 1.2-centimeter-diameter bar. Nine of the alloys cracked during rolling at 1100° C or even at 1200° C. All cracked alloys contained high levels of molybdenum, aluminum, and/or silicon (table I), all of which are known to result in fabrication problems (refs. 1 and 5). However, specimens were machined from cast buttons of three of these unrollable alloys.

Two of the alloys were chemically analyzed to determine how accurate the nominal compositions were and to determine the levels of interstitial elements. The results are shown in table II and indicate that the nominal compositions are indeed quite accurate. Interstitial concentrations determined in these two experimental titanium alloys are all within the ranges reported previously (ref. 8) for commercial titanium alloys. The iron contents were slightly higher in the experimental alloys than in commercial alloys.

Selected alloys were examined both metallographically and by X-ray diffraction. Representative photomicrographs of longitudinal sections of the titanium-vanadium series of alloys are shown in figure 1. Alloys exhibited a typical hot-worked structure of elongated grains and occasional stringers of impurities, possibly oxides (figs. 1(b) and (e)). Although X-ray diffraction indicated that all alloys were single-phase beta, metallographic examination indicated the possible existence of a small amount of alpha or omega phase in those alloys with the lowest amount of beta stabilizer, Ti-25Mo, Ti-25Nb, and Ti-25V (fig. 1(a)), and in those alloys with large amounts of aluminum (fig. 1(f)). All silicon-containing alloys had dispersed silicide particles which also tended to concentrate at grain boundaries (figs. 1(c), (d), (g), and (h)).

Specimens

The specimen geometry used in this investigation for both tensile and creep testing is shown in figure 2. Specimens were machined from the as-rolled or as-cast material and received no treatment other than degreasing before tensile and creep testing.

Test Procedure

Tensile tests were conducted at 23°, 500°, and 650° C in air at a crosshead speed of 0.1 centimeter per minute. All elongation data were determined over a

2.5-centimeter gage length. All tensile properties determined are listed in table I. Specimens were subjected to creep in air for 100 hours at 500° and 650° C at stresses ranging from 70 to 690 MN/m^2 (10 to 100 ksi) in increments of 70 MN/m^2 (10 ksi). Stress levels required to cause 1 percent creep elongation in 100 hours were estimated from the elongation of specimens measured after creep exposure. Post-creep tensile tests were conducted on creep-exposed specimens at 23° C to determine residual tensile properties. Creep and post-creep data are listed in tables III and IV.

RESULTS AND DISCUSSION

Initial Screening

Initial screening of 12 alloy compositions consisted of tensile testing at 23°, 500°, and 650° C. The results of these tests are plotted in figure 3 on a density-corrected basis for comparative purposes.

The titanium-niobium binary and ternary alloys appear to offer the least potential for elevated-temperature capability. The Ti-25Nb binary alloy had better strength than the other five titanium-niobium alloys to about 550° C. Only at a test temperature of 650° C did ternary additions of molybdenum, vanadium, or aluminum result in any improvement in tensile strength compared to the binary alloy. The two titanium-molybdenum alloys tested (Ti-25Mo and Ti-20Mo-25V) had fairly good tensile strengths over the range of temperatues investigated. However, all these niobium and molybdenum additions to titanium resulted in severe density penalties.

It is evident that the titanium-vanadium series of alloys offers the most potential for further alloying development based on either the density-corrected strengths presented in figure 3 or the actual strength levels listed in table I. Specifically, increasing the vanadium content of a titanium-vanadium binary alloy from about 25 to 50 percent resulted in substantial improvements in tensile strength over the entire range of temperatures investigated. More importantly, additions of 2 percent silicon and 5 percent aluminum resulted in dramatic increases in strength to about 600° C. Further compositional modifications of this promising system are described in the succeeding sections of this report.

Compositional Modifications of Titanium-Vanadium Alloys

Modifications of the Ti-50V base alloy were conducted by systematically varying both aluminum and silicon contents. Data are cross-plotted in figures 4 and 5 to illustrate the separate effects of aluminum and silicon on the 23° C tensile properties of the base alloy. Similarly, the effects of aluminum and silicon content on the 500° C tensile properties of the base alloy are cross-plotted in figures 6 and 7.

Tensile properties of Ti-V-Si alloys at 23° C. - The effect of aluminum additions to a series of Ti-50V-Si alloys was studied by systematically varying the aluminum content from 0 to 7 percent. Both the ultimate tensile strength and reduction of area of these alloys and of the baseline Ti-50V alloy are presented in figure 4.

Data for the Ti-50V and the Ti-50V-2Si alloys suggest that alloy softening may occur at an aluminum content of approximately 1 percent. A similar effect has been reported for a Ti-55Ni-0.2Al alloy (ref. 9) and is well known to occur in some refractory metal alloys. For the alloys shown in figure 4, increasing aluminum content, in the range 1 to approximately 5 percent, resulted in increased strength and decreased ductility for all alloys tested. Aluminum contents near 7 percent resulted in severe embrittlement of the Ti-50V alloy, as evidenced by premature tensile failure and almost no ductility. Presumably, aluminum contents near 7 percent would also result in similar behavior for the titanium-vanadium-silicon alloys.

Alloys with good strength and a minimum of approximately 10 percent ductility had silicon contents of 1 to 2 percent and aluminum contents of 2 to 4 percent.

Tensile properties of Ti-V-Al alloys at 23° C. - The effect of silicon additions to a series of titanium-vanadium-aluminum alloys was studied by varying the silicon content from 0 to 2 percent. The ultimate tensile strength and reduction of area of these alloys, and of the baseline Ti-50V alloy, are shown in figure 5.

Silicon was a potent strengthener, with maximum tensile strength occurring at a silicon content of about 2 percent in the baseline Ti-50V alloy. However, silicon additions generally resulted in reduced ductility, particularly when added to the Ti-50V-5Al alloy.

As previously noted, alloys with good strength and a minimum of 10 percent ductility had silicon contents of 1 to 2 percent and aluminum contents of 2 to 4 percent.

Tensile properties of Ti-V-Si alloys at 500° C. - The tensile strength and ductility of the titanium-vanadium-silicon series of alloys at 500° C are presented in figure 6. The general behavior at 500° C is quite similar to that observed at 23° C (compare fig. 6 with fig. 4). Specifically, data for the Ti-50V and Ti-50V-2Si alloys suggest that alloy softening may occur with an aluminum content of about 1 percent. Aluminum contents of 1 to about 5 percent resulted in increased strength and decreased ductility for all compositions tested. In the baseline Ti-50V alloy, an increase in aluminum content from 5 to 7 percent resulted in a decrease in tensile strength and a continuation of the trend of decreased ductility observed at lower aluminum contents.

All compositions tested had at least 18 percent reduction of area. The alloys that exhibited the highest strengths were those with silicon contents of 1 to 2 percent and aluminum contents of 3 to 5 percent.

Tensile properties of Ti-V-Al alloys at 500° C. - The tensile strength and ductility of the titanium-vanadium-aluminum series of alloys at 500° C are presented in figure 7. Once again solution softening appears to occur with a silicon content of about 0.5 percent, followed by increased strength and decreased ductility to a silicon content of about 2 percent. For the baseline Ti-50V alloy, property trends reversed at the highest silicon content, 3 percent.

All compositions tested exhibited at least 18 percent reduction of area. The alloys with highest strength levels were those with silicon contents of 1 to 2 percent and aluminum contents of 3 to 5 percent.

Tensile properties of Ti-V alloys at 650° C. - The limited test data shown in figure 3 indicated a dramatic fall-off in the tensile strength of the Ti-50V-2Si and Ti-50V-5Al alloys near 650° C. Additional ternary and quaternary alloy compositions have been tested at 650° C and confirm this behavior. Not all compositions were tested at 650° C, but it appears from the data shown in table I that compositions studied in this investigation in the hot-rolled conditions all exhibited a substantial decrease in tensile strength as the test temperature was increased from 500° to 650° C. Concurrent with decreased tensile strength, the alloys tested were extremely ductile with reductions of area typically in the range 70 to 90 percent.

Comparison of Ti-V alloys with commercial alloys. - Perhaps the most meaningful way of comparing the tensile properties of the experimental titanium-vanadium alloys described in the previous sections of this report with the tensile properties of commercial titanium alloys is on a density-corrected basis, as shown in figure 8. Four of the experimental alloys are compared with four commercial titanium alloys (refs. 10 and 11).

It is apparent from figure 8 that the experimental titanium-vanadium alloys have specific tensile strengths equivalent to those of the commercial titanium alloys at 23° C. At both 500° and 650° C the experimental alloys had specific tensile strengths significantly greater than those of the commercial titanium alloys. For example, the specific tensile strength of the Ti-50V-5Al-2Si alloy at 500° C was 25 percent greater than that of the strongest commercial titanium alloy. Likewise, at 650° C the specific tensile strength of the Ti-50V-5Al-1Si alloy was about 14 percent greater than that of the strongest commercial titanium alloy.

Creep strength of Ti-V alloys. - An extensive investigation of the creep strength of ternary and quaternary titanium-vanadium alloys was conducted at 500° C. All creep-exposure conditions and amounts of creep deformation are listed in table III. Both ternary series of alloys, titanium-vanadium-silicon and titanium-vanadium-aluminum, had low creep strengths. Exposures at stresses of 345 to 415 MN/m^2 (50 to 60 ksi) resulted in substantial amounts of creep deformation for all these alloys.

The quaternary series of alloys, titanium-vanadium-aluminum-silicon, had the best creep resistance of all alloys studied in this investigation. Many of the alloys exhibited only small amounts of creep deformation within 100 hours at stresses of 415 to 550 MN/m^2 (60 to 80 ksi). The alloy with the greatest creep strength was Ti-50V-3Al-1Si.

A limited amount of creep-exposure testing was also conducted at 650° C (table IV). Attention was focused primarily on those alloys which had fairly high creep strength at 500° C. The Ti-50V-3Al-1Si alloy was also the one with the best creep resistance at 650° C.

Approximate 100-hour 1-percent-creep elongation and 100-hour-rupture strengths for the Ti-50V-3Al-1Si alloy are plotted in figure 9. For comparison purposes, similar data are shown for the commonly used Ti-6Al-4V alloy and the more recently developed, high-creep-strength Ti-11 and Ti-5Al-6Sn-2Zr-1Mo-0.2Si alloys. As evident from figure 9(a), the creep strength of the experimental titanium alloy is far superior to that of the Ti-6Al-4V alloy and almost equivalent to that of the most creep-resistant commercial titanium alloys. Even when corrected for its 12 percent greater density (fig. 9(b)), the experimental titanium alloy compares favorably with the commercial titanium alloys, Ti-5621S and Ti-11.

Creep stability of Ti-V alloys. - In addition to high creep strength, structural alloys must be metallurgically stable. Service exposures at elevated temperatures frequently result in the decomposition or precipitation of metallurgical phases which are manifested by reduced ductility. In order to determine the effects of creep exposure on the mechanical properties of the experimental alloys studied in this investigation, they were tensile tested at room temperature after the 100-hour creep exposure.

Although all alloys tested in this investigation exhibited less ductility after creep exposure than in the as-rolled condition, several of the alloys retained sufficient ductility to be considered for structural use. For example, the alloy that exhibited the highest creep strength, Ti-50V-3Al-1Si, exhibited 5 percent elongation after 100 hours of creep exposure at either 500° or 650° C as compared with 10 percent elongation in the as-rolled condition (fig. 10). Several other titanium-vanadium alloys with silicon contents of 1 to 1.5 percent and aluminum contents of 1 to 3 percent had about 5 percent elongation after creep exposures. Alloys with higher silicon or aluminum contents had less than 5 percent elongation after creep exposure. (See tables III and IV for all test results.)

Once again a comparison between these experimental titanium alloys and commercial titanium alloys is appropriate. Post-exposure tensile data for Ti-11 and Ti-5621S from reference 10 are also shown in figure 10. The creep exposures shown for these two commercial titanium alloys were chosen from the limited data in the literature (ref. 10) as the creep exposure conditions nearest to those used in this investigation for the experimental titanium alloys. As evident from figure 10, metallurgical stability is also a severe problem in these commercial titanium alloys. Ductility losses of the same magnitude occur for these commercial alloys, as was discussed in the previous section of this report for the experimental titanium-vanadium alloys.

It should be pointed out that the data obtained in this investigation and those shown in figure 10 from the literature were obtained on specimens with the surfaces in the creep-exposed condition. Since the outer surface layers of the specimens were not machined off, no attempt can be made to separate the roles of metallurgical stability and oxygen contamination in reducing alloy ductility.

CONCLUDING REMARKS

It should be emphasized that the alloys tested in this investigation were in the as-rolled, or in a few instances the as-cast, condition. No attempts were made to heat treat the alloys. Obviously, it is safe to assume that optimum metallurgical aspects, such as grain size and precipitate concentration, size, and morphology were not obtained. In addition, no hot or cold mechanical working treatments were used. The use of such treatments in combination with judicious choices of other alloying elements and refinement of the concentration levels for the alloying elements used in this study have the potential for increasing strength and stability.

From the limited data obtained in this study, titanium-niobium and titanium-molybdenum base alloys do not appear to be candidate alloys for compressor components or for other structural uses at elevated temperatures, primarily because of their low strength coupled with high density. However, titanium-vanadium alloys have high strength and are only about 12 percent denser than commercial titanium alloys. Furthermore, it is suggested that the Ti-50V base alloy has additional potential for both solid solution and precipitation strengthening. Beta titanium-vanadium alloys are worthy of additional research aimed at their use as turbine engine compressor components, as well as for other elevated-temperature structural applications.

SUMMARY OF RESULTS

Tensile and creep properties of five series of experimental beta-phase titanium alloys were determined. The alloy series were titanium-niobium, titanium-molybdenum, titanium-vanadium-silicon, titanium-vanadium-aluminum, and titanium-vanadium-aluminum-silicon. Alloys were tested in the as-rolled condition, with the exception of a few compositions that were tested in the as-cast condition because they cracked during rolling. Alloys were tensile tested at 23°, 500°, and 650° C. Alloys were creep tested for 100 hours at 500° and 650° C. Post-creep tensile tests were conducted at 23° C to determine the residual tensile properties of the alloys.

The major results of this exploratory investigation are as follows:

1. The titanium-vanadium series of alloys had substantially greater tensile and creep strength than any of the titanium-niobium and titanium-molybdenum alloys tested.

2. The specific tensile strengths of Ti-50V-(3 to 5)Al-(1 to 2)Si alloys were equivalent to those of commercial titanium alloys at 23° C and superior to those of commercial titanium alloys in the temperature range 500° to 650° C.

3. The Ti-50V-3Al-1Si alloy had the best balance of tensile strength, creep strength, and metallurgical stability.

4. The creep strength of the Ti-50V-3Al-1Si alloy is far superior to that of a commonly used commercial titanium alloy, Ti-6Al-4V, at 500° C. The creep strength of this experimental alloy is almost equivalent to that of two newly developed commercial titanium alloys, Ti-5621S and Ti-11.

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National Aeronautics and Space Administration,
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505-01.

REFERENCES

1. Rostoker, W.; Yamamoto, A. S.; and Riley, R. E.: The Mechanical Properties of Vanadium-Base Alloys. Trans. ASM, vol. 48, 1956, pp. 560-578.

2. Adenstedt, H. K.; Pequignot, J. R.; and Raymer, J. M.: The Titanium-Vanadium System. Trans. ASM, vol. 44, 1952, pp. 990-1003.

3. Hunter, D. B.: Screening and Selection of Candidate Sheet Alloys. II. Titanium Metals Corp. of America (WALTR-405/2-15; AD-648245), 1966.

4. Boyd, J. D.; Haynie, F. H.; Moreland, P. J.; Boyd, W. K.; Wood, R. A.; Williams, D. N.; and Jaffee, R. I.: The Effect of Composition on the Mechanism of Stress-Corrosion Cracking of Titanium Alloys in N_2O_4, and Aqueous and Hot-Salt Environments. (Battelle Memorial Institute; NASr-100(09)), NASA CR-96023, 1968.

5. Crossley, F. A.; and Kessler, H. D.: Titanium Alloys Give Promise of High Temperature Applications. J. Metals, vol. 6, no. 2, Feb. 1954, pp. 119-121.

6. DeLazaro, D. J.; and Rostoker, W.: Correlation Between Heat Treatment, Microstructure and Mechanical Properties of Titanium-Molybdenum Alloys. Trans. ASM, vol. 46, 1954, pp. 292-311.

7. Berger, L. W.; Williams, D. N.; and Jaffee, R. I.: Mechanical Properties and Heat Treatment of Titanium-Niobium Alloys. Trans. ASM, vol. 50, 1958, pp. 384-397.

8. Gray, Hugh R.: Effects of Hot-Salt Stress Corrosion on Titanium Alloys. Metals Eng. Quart., vol. 12, no. 4, Nov. 1972, pp. 10-17.

9. Garfinkle, Marvin: Exploratory Study of Elevated-Temperature Tensile Properties of Alloys Based on the Intermetallic Compound TiNi. Met. Trans., vol. 5, no. 11, Nov. 1974, pp. 2383-2388.

10. Wood, Richard A.; and Favor, Ronald J.: Titanium Alloys Handbook. MCIC-HB-02, Metals and Ceramics Information Center, Battelle Memorial Institute (AD-758335), 1972.

11. Weiss, V.; and Sessler, J. G., eds.: Aerospace Structural Materials Handbook. AFML-TR-68-115, revision, Syracuse Univ. Press, 1973.

TABLE I. - TENSILE TEST DATA

Nominal composition, wt %	Density, g/cm^3	Test temperature, °C											
		23				500				650			
		Ultimate tensile strength		Reduction of area, percent	Elongation, percent	Ultimate tensile strength		Reduction of area, percent	Elongation, percent	Ultimate tensile strength		Reduction of area, percent	Elongation, percent
		MN/m^2	ksi			MN/m^2	ksi			MN/m^2	ksi		
Ti-25Nb	5.0	820	119	11	8	585	85	46	19	165	24	96	62
Ti-50Nb	5.8	515	75	84	26	235	34	85	25	165	24	96	70
Ti-25Nb-25V	5.5	815	118	43	16	595	86	63	26	370	54	94	105
Ti-25Nb-25Mo	6.1	905	131	46	19	640	93	74	24	495	72	84	33
Ti-40Nb-2Si	5.3	705	102	12	8	285	41	62	25	165	24	86	59
Ti-50Nb-2Si[a]	5.7	---	---	--	--	550	80	12	8	---	---	--	---
Ti-50Nb-5Al	5.5	815	118	43	78	635	92	50	21	455	66	87	39
Ti-25Mo	5.3	785	114	62	23	460	67	76	20	285	41	94	93
Ti-40Mo	5.9	---	---	--	--	690	100	52	19	---	---	--	---
Ti-50Mo[b]	6.2	---	---	--	--	---	---	--	--	---	---	--	---
Ti-20Mo-25V	5.5	980	142	20	6	605	88	17	5	---	---	--	---
Ti-25Mo-25V[a]	5.7	---	---	--	--	760	110	15	5	---	---	--	---
Ti-40Mo-2Si[a]	5.8	---	---	--	--	310	45	1	0	---	---	--	---
Ti-50Mo-2Si[b]	6.1	---	---	--	--	---	---	--	--	---	---	--	---
Ti-50Mo-5Al[b]	6.0	---	---	--	--	---	---	--	--	---	---	--	---
Ti-40Mo-5Al[b]	5.7	---	---	--	--	---	---	--	--	---	---	--	---
Ti-25V	4.9	695	101	27	13	415	60	65	75	170	25	96	140
Ti-50V	5.2	815	118	45	18	670	97	41	21	490	71	86	58
						725	105	42	20				
Ti-50V-1Si	5.2	915	133	32	15	770	112	59	28	530	79	72	32
Ti-50V-1.5Si	5.2	1060	153	15	5	850	123	41	21	---	---	--	---
Ti-50V-2Si	5.1	1190	173	11	3	1010	146	19	10	475	69	99	160
						1030	149	25	14				
Ti-50V-3Si[c]	5.1	1020	148	20	13	825	120	46	22	540	78	84	52
Ti-50V-1Al	5.2	870	126	57	20	650	94	56	17	560	81	74	42
Ti-50V-3Al	5.1	970	141	38	11	805	117	49	21	615	89	73	32
Ti-50V-5Al	5.0	1080	156	28	22	945	137	27	18	580	84	79	44
						960	139	28	20				
Ti-50V-7Al	4.9	690	100	1	1	870	126	16	7	740	107	77	57
Ti-35V-3Al-1.5Si	4.8	985	143	14	13	795	115	62	33	305	44	91	79
Ti-42V-3Al-1.5Si	4.9	1030	150	11	12	875	127	34	24	430	62	89	78
Ti-50V-3Al-1.5Si	5.0	1170	169	15	10	1030	150	18	18	---	---	--	---
Ti-50V-3Al-1.0Si	5.1	1100	159	13	10	980	142	20	20	585	85	80	68
Ti-50V-3Al-1.2Si	5.1	1140	165	16	10	1000	145	24	18	565	82	83	56
Ti-50V-3Al-1.8Si	5.0	1190	172	11	8	1080	156	18	19	---	---	--	---
Ti-50V-5Al-0.5Si	5.0	1030	150	1	1	910	132	40	17	585	85	78	72
Ti-50V-5Al-1Si	5.0	1160	168	4	1	1010	147	21	14	785	114	54	34
Ti-50V-5Al-2Si	5.0	1270	184	6	5	1120	163	18	12	660	96	68	53
Ti-50V-5Al-3Si[a]	4.9	----	---	--	--	----	---	--	--	---	---	--	---
Ti-50V-1Al-2Si	5.1	1030	150	22	14	835	121	53	23	540	78	89	53
Ti-50V-1.7Al-1.5Si	5.1	1060	154	9	7	930	135	24	19	---	---	--	---
Ti-50V-2.3Al-1.5Si	5.0	1120	162	15	10	995	144	25	19	---	---	--	---
Ti-50V-3.4Al-1.5Si	5.0	1210	175	11	10	1090	158	19	16	620	90	83	64
Ti-50V-4.0Al-1.5Si	5.0	1220	177	9	5	1100	160	18	12	640	93	77	51
Ti-50V-7Al-2Si[b]	4.9	----	---	--	--	----	---	--	--	---	---	--	---

[a]Nonrollable at 1100° and 1200° C; specimens machined from cast buttons.
[b]Nonrollable at 1100° and 1200° C; no specimens obtainable.
[c]Nonrollable at 1100° C; rollable at 1200° C.

TABLE II. - COMPOSITION OF TITANIUM ALLOYS

Alloy		Ti	V	Al	Si	Fe	C	N	O	H
		Composition, wt %								
Experimental alloys	Ti-50V-3Al-1.0Si analyzed	47.0	48.5	3.4	1.00	0.2	0.0165	0.0143	0.144	0.0074
	Ti-50V-3Al-1.0 nominal	Bal.	50	3	1.0	---	------	------	------	------
	Ti-50V-3Al-1.2Si analyzed	46.1	47.6	3.1	1.23	.2	.0166	.0151	.156	.0085
	Ti-50V-3Al-1.2Si nominal	Bal.	50	3	1.2	---	------	------	-----	------
Commercial alloys[a]	Ti-5621S	Bal.[b]	0	5.0	.28	.03	.02	.006	.10	.0056
	Range for eight typical alloys	Bal.[b]	0 - 13	2 - 8	0 - 0.3	0.03 - 0.13	0.01 - 0.02	0.006 - 0.026	0.07 - 0.15	0.0036 - 0.0104

[a]Vendor-certified analyses (ref. 8).
[b]May include Sn, Zr, Mo, and/or Cr (ref. 8).

TABLE III. - 500° C CREEP AND POST-CREEP DATA

Nominal composition, wt %	500° C Creep exposure					Post-creep tensile test at 23° C[a]			
	Stress		Time, hr	Reduction of area, percent	Elongation, percent	Ultimate tensile strength		Reduction of area, percent	Elongation, percent
	MN/m^2	ksi				MN/m^2	ksi		
Ti-40Mo[b]	205	30	100	0	0	340	49	0	0
Ti-40Mo	345	50	48	8.1	1	----	---	--	--
Ti-20Mo-25V	205	30	72	9.4	2	----	---	--	--
Ti-50V	205	30	100	19	19	815	118	30	9
	205	30	100	6.9	9	800	116	30	14
Ti-50V-1Si	345	50	97	20	20	925	134	12	5
Ti-50V-1.5Si	345	50	100	.8	3	1030	150	9	4
Ti-50V-2Si	415	60	100	9.0	8	970	141	2	1
Ti-50V-3Si	415	60	100	1.6	2	1030	149	3	1
Ti-50V-1Al	275	40	100	32	38	850	123	25	6
Ti-50V-3Al	345	50	100	4.4	7	1290	187	14	7
Ti-50V-5Al	345	50	83	2.8	3	----	---	--	--
Ti-50V-7Al[c]	205	30	100	<2.8	<1	----	---	--	--
	310	45	6	0	0	----	---	--	--
Ti-50V-7Al	415	60	2	0	0	----	---	--	--
Ti-35V-3Al-1.5Si	275	40	52	20	9	----	---	--	--
	345	50	7	17	10	----	---	--	--
Ti-42V-3Al-1.5Si	345	50	100	2.0	1	1150	167	7	4
	415	60	81	7.9	2	----	---	--	--
Ti-50V-3Al-1.5Si	415	60	100	2.5	4	1260	182	5	2
	485	70	58	4.8	3	----	---	--	--
Ti-50V-3Al-1.0Si	415	60	100	0	0	1190	173	4	5
	485	70	100	1.0	0	1210	176	6	5
	550	80	93	4.8	2	----	---	--	--
Ti-50V-3Al-1.2Si	415	60	100	1.9	1	1250	181	4	4
	485	70	100	1.9	2	1300	188	6	6
	550	80	21	3.5	1	----	---	--	--
Ti-50V-3Al-1.8Si	415	60	100	4.8	4	1420	206	1	1
	485	70	28	4.8	3	----	---	--	--
Ti-50V-5Al-0.5Si[d]	415	60	120	1.3	1	470	68	1	1
Ti-50V-5Al-1Si	415	60	100	32	29	590	86	0	0
	485	70	95	1.0	2	----	---	--	--
Ti-50V-5Al-2Si	485	70	40	2.0	3	----	---	--	--
	550	80	42	.6	1	----	---	--	--
	550	80	49	1.5	2	----	---	--	--
Ti-50V-5Al-3Si[c]	415	60	3	1.9	0	----	---	--	--
Ti-50V-1Al-2Si	345	50	100	1.0	1	1060	154	7	5
	415	60	75	13	6	----	---	--	--
Ti-50V-1.7Al-1.5Si	345	50	100	1.0	1	1140	165	6	4
	415	60	11	8.0	4	----	---	--	--
Ti-50V-2.3Al-1.5Si	345	50	100	0	0	1150	167	4	4
	415	60	100	3.2	1	1230	178	3	4
	485	70	100	2.2	3	1240	180	6	2
	550	80	83	8.2	24	----	---	--	--
Ti-50V-3.4Al-1.5Si	415	60	100	2.1	1	1670	235	3	3
Ti-50V-3.4Al-1.5Si[c]	415	60	58	1.9	0	----	---	--	--
Ti-50V-3.4Al-1.5Si	485	70	74	1.3	0	----	---	--	--
	690	100	3	4.1	1	----	---	--	--
Ti-50V-4Al-1.5Si	345	50	100	1.5	1	1650	239	1	1
	415	60	70	1.0	3	----	---	--	--
	485	70	87	1.9	3	----	---	--	--

[a]No tensile data means specimen failed in creep test.

[b]Failed outside of gage during tensile test.

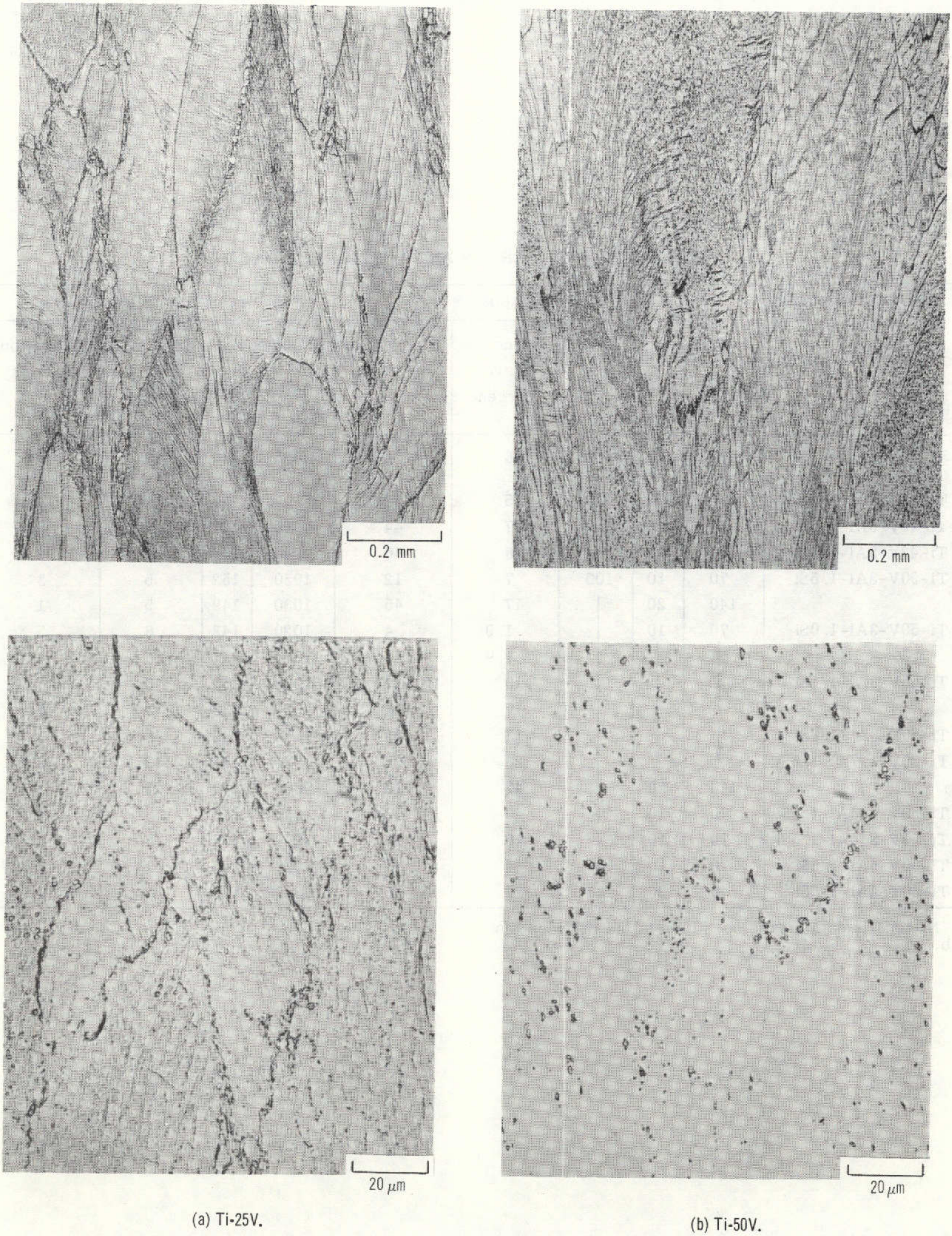
[c]Failed outside of gage during creep test.

[d]Unintentionally long creep test.

TABLE IV. - 650° C CREEP AND POST-CREEP DATA

Nominal composition, wt %	650° C Creep exposure					Post-creep tensile test at 23° C[a]			
	Stress		Time, hr	Reduction of area, percent	Elongation, percent	Ultimate tensile strength		Reduction of area, percent	Elongation, percent
	MN/m^2	ksi				MN/m^2	ksi		
Ti-50V-3Al	70	10	100	28	36	925	134	21	9
Ti-35V-3Al-1.5Si	70	10	39	75	60	---	---	--	--
Ti-42V-3Al-1.5Si	70	10	100	27	44	840	122	21	5
Ti-42V-3Al-1.5Si[b]	140	20	4	28	40	940	136	4	2
Ti-50V-3Al-1.5Si	70	10	100	7	12	1050	152	5	3
	140	20		17	45	1030	149	5	1
Ti-50V-3Al-1.0Si	70	10		1.9	4	1020	148	6	5
				1.9	4	1010	147	6	4
Ti-50V-3Al-1.2Si				10	7	1030	150	5	4
				17	26	915	133	13	2
Ti-50V-3Al-1.8Si				13	21	1030	149	6	3
Ti-50V-1.7Al-1.5Si				23	28	930	135	12	5
	140	20		42	78	800	116	27	1
Ti-50V-2.3Al-1.5Si	70	10		40	40	1010	147	5	4
Ti-50V-3.4Al-1.5Si	70	10		10	12	1050	152	3	3
Ti-50V-4Al-1.5Si	70	10		4	5	1060	153	1	1
Ti-50V-4Al-1.5Si[b]	140	20	63	27	40	1050	152	3	1

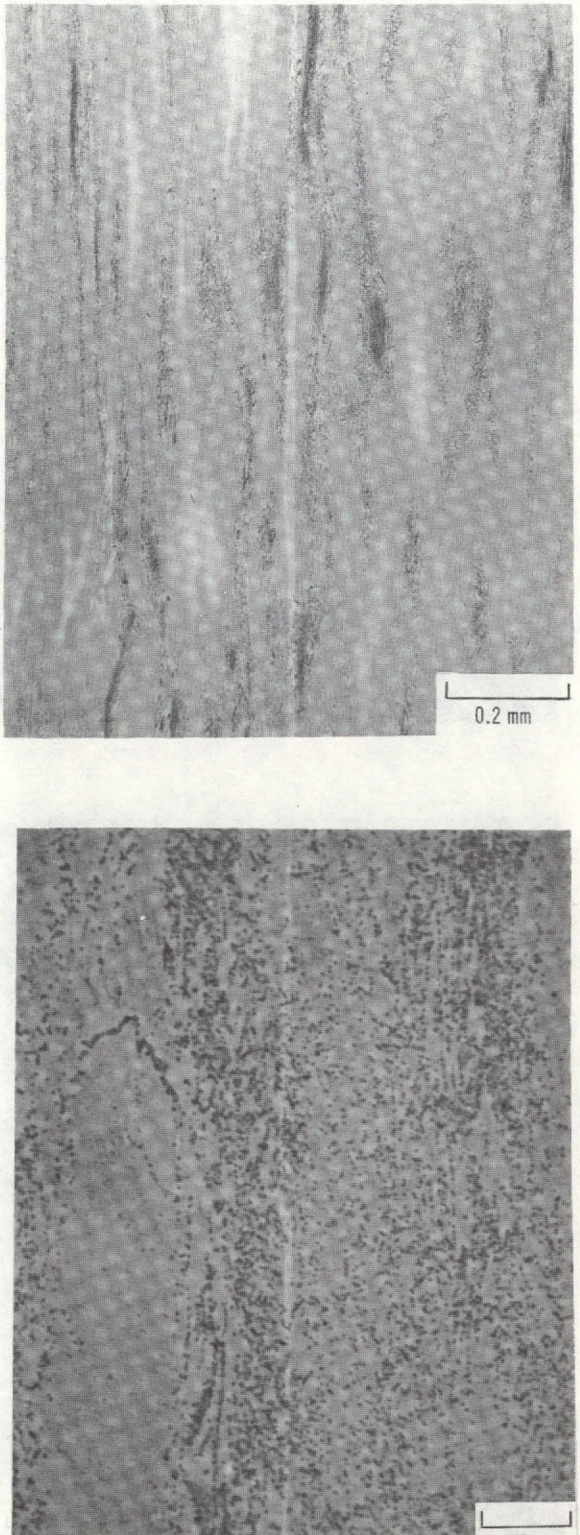
[a]No tensile data means specimen failed in creep test.
[b]"Bottomed out" during creep test.



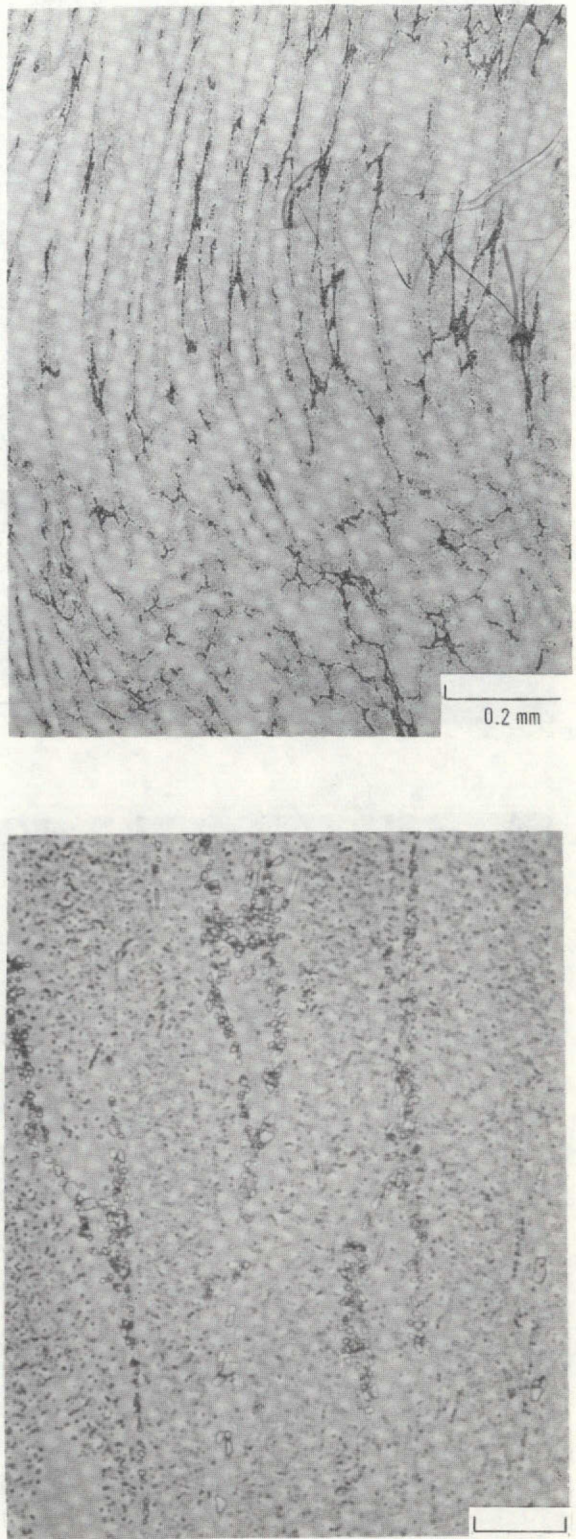
(a) Ti-25V.

(b) Ti-50V.

Figure 1. - Photomicrographs of a series of experimental titanium-vanadium alloys.

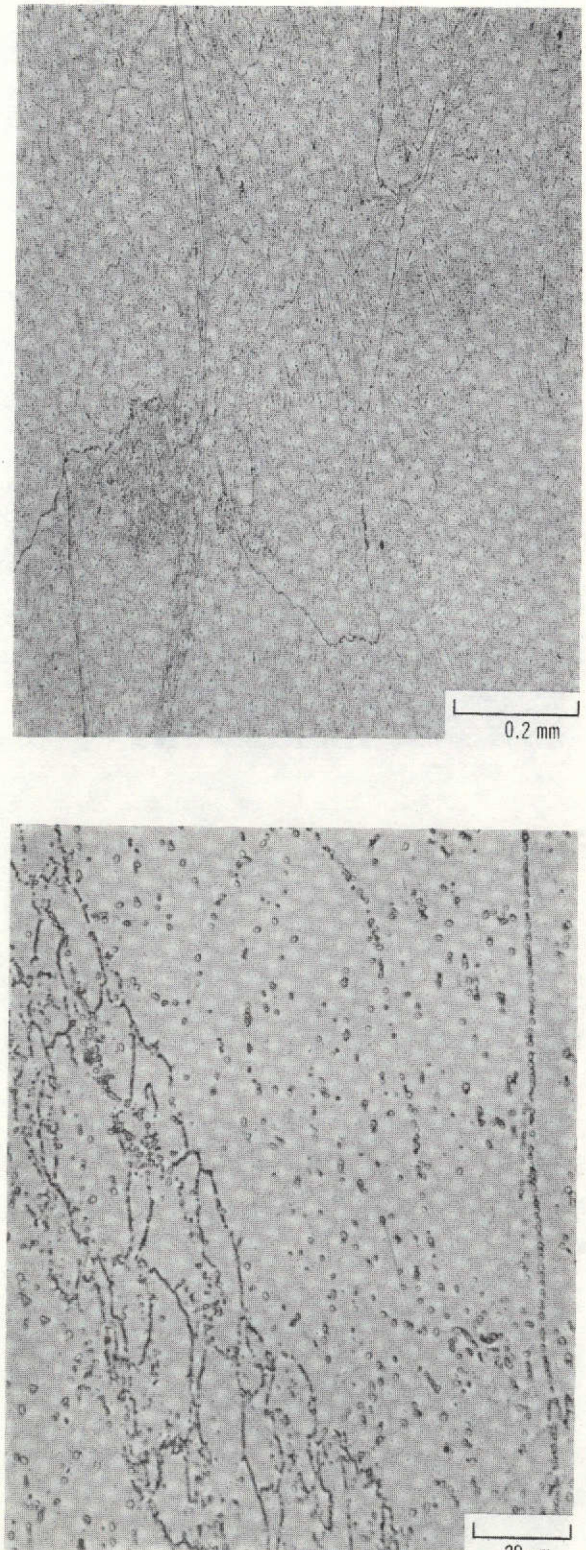


(c) Ti-50V-1Si.

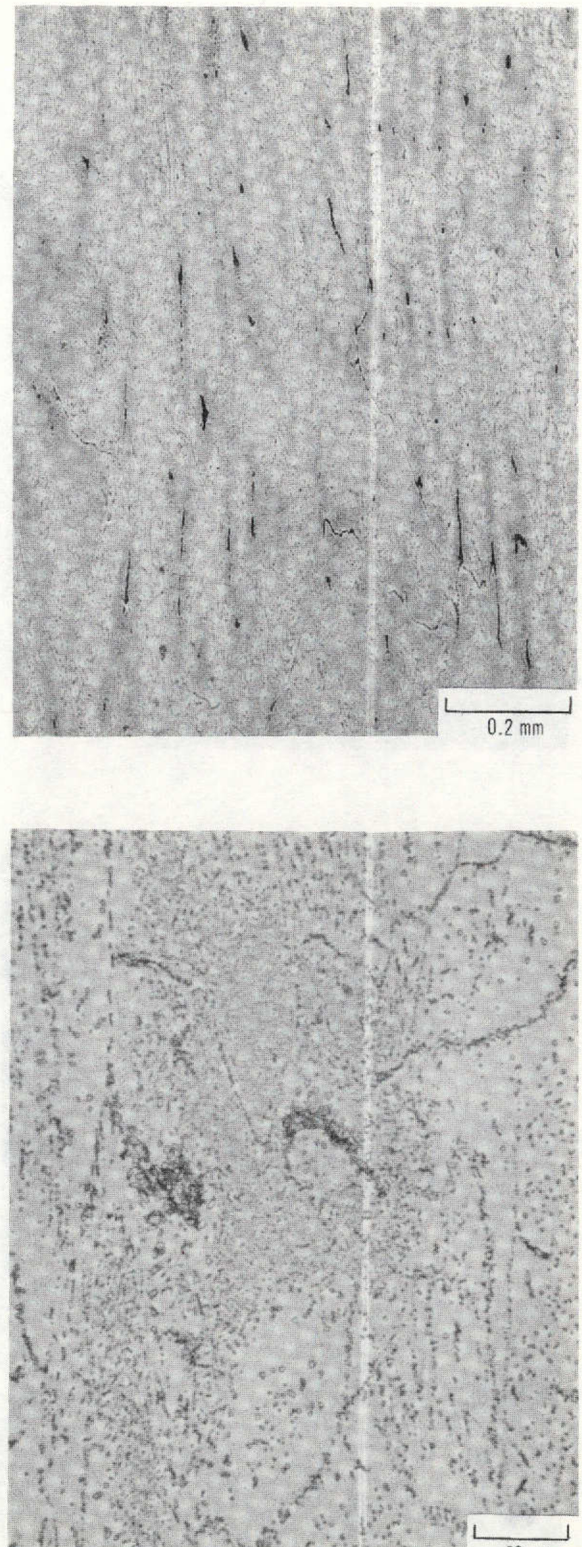


(d) Ti-50V-3Si.

Figure 1. - Continued.

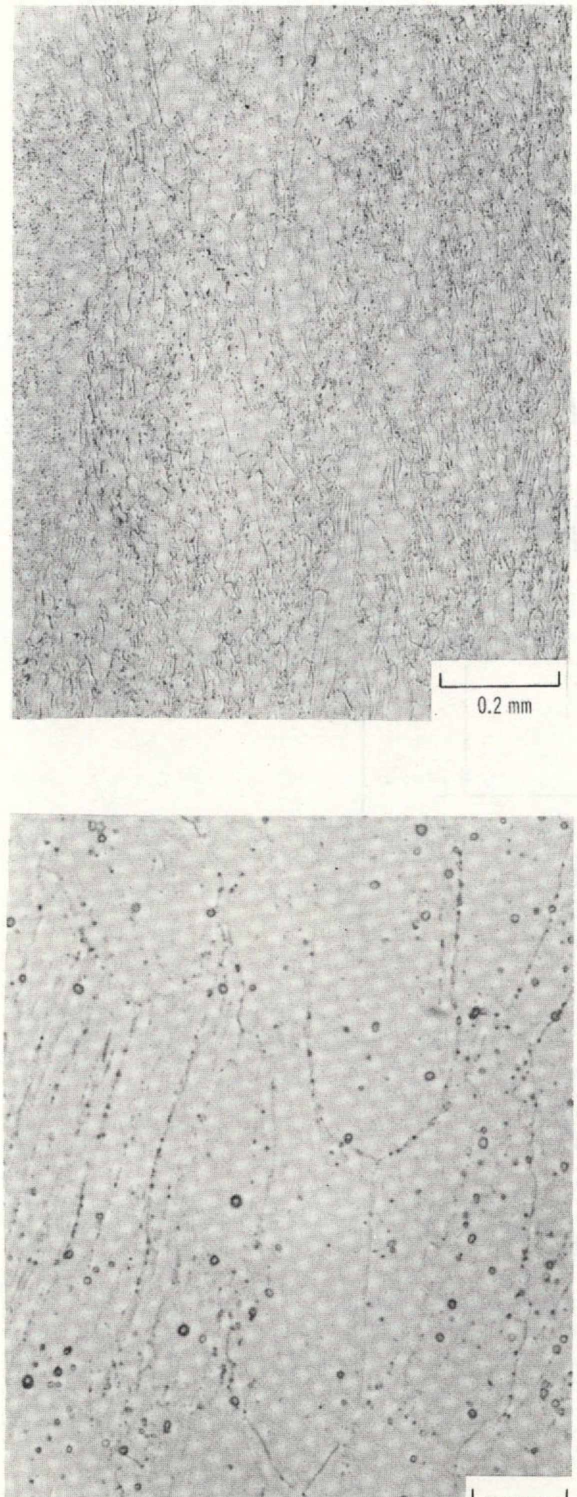


(g) Ti-50V-3Al-1Si.

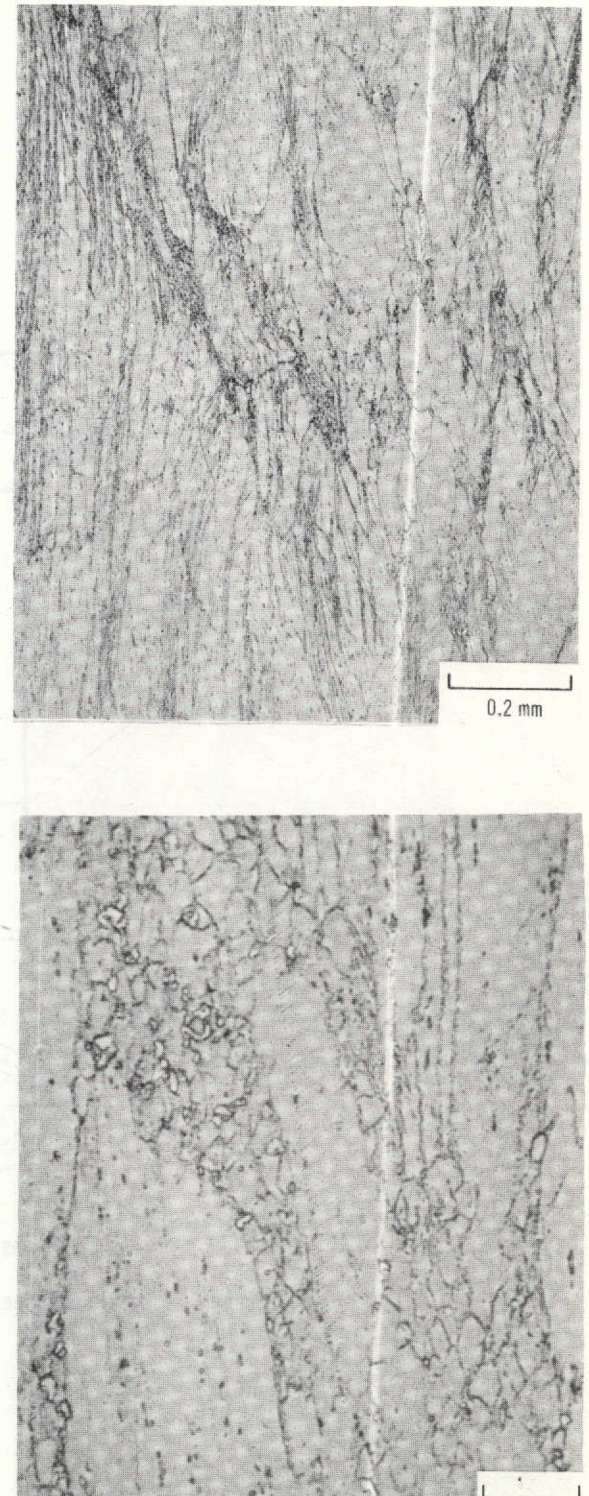


(h) Ti-50V-5Al-2Si.

Figure 1. - Concluded.



(e) Ti-50V-1Al.



(f) Ti-50V-5Al.

Figure 1. - Continued.

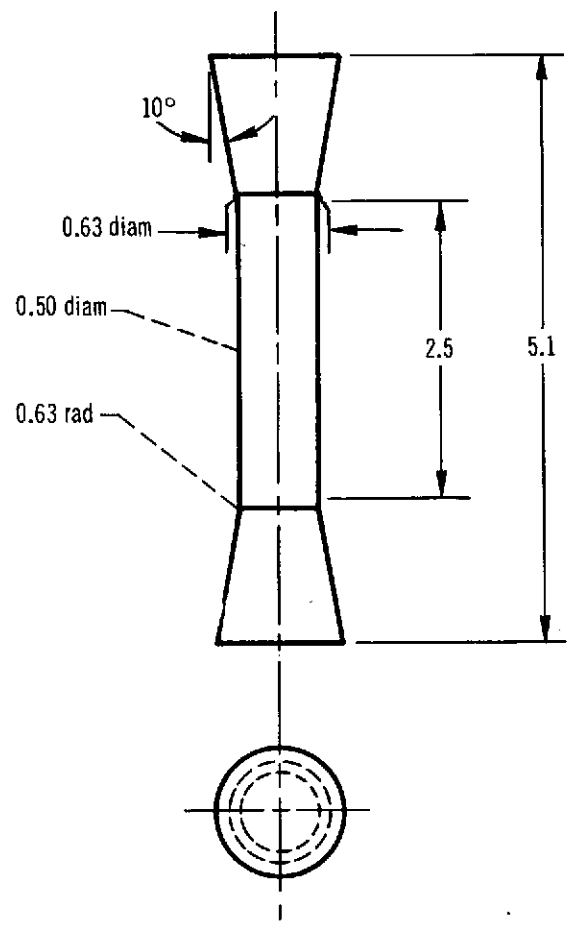


Figure 2. - Tensile and creep specimen used in this investigation. (Dimensions are in cm.)

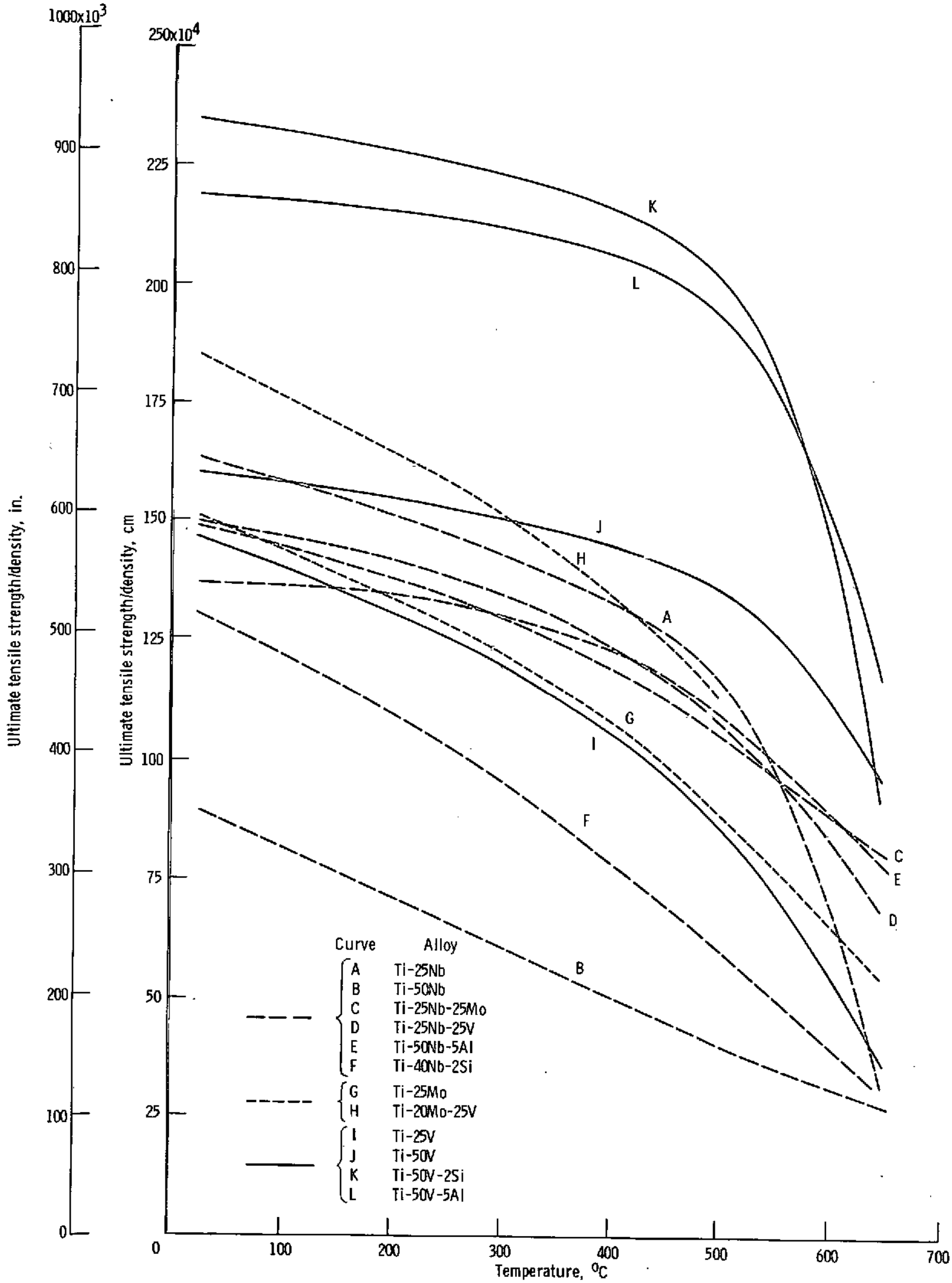


Figure 3. - Specific tensile strength of experimental titanium alloys.

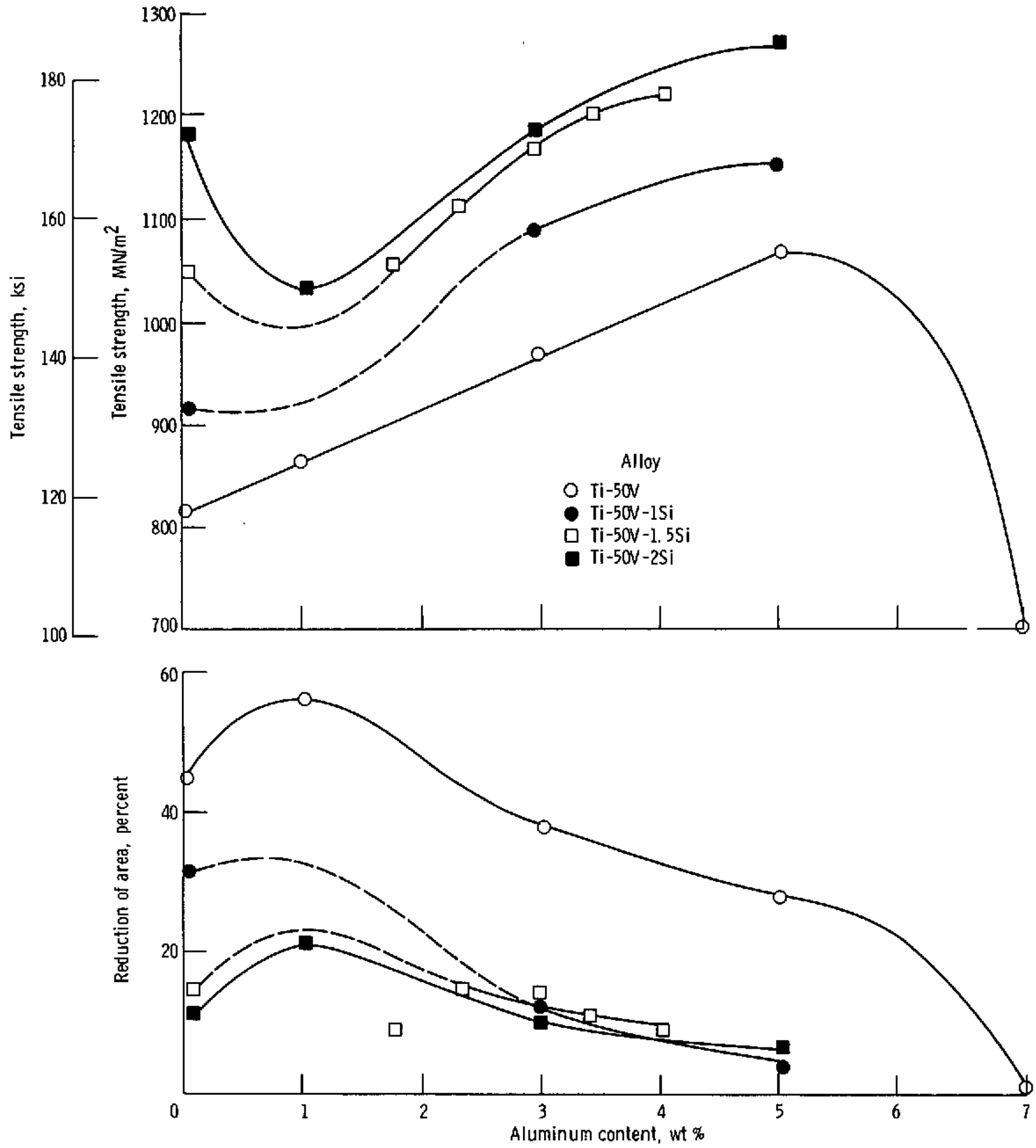


Figure 4. - Effect of aluminum content on tensile properties at 23^{0} C of titanium-vanadium-silicon alloys.

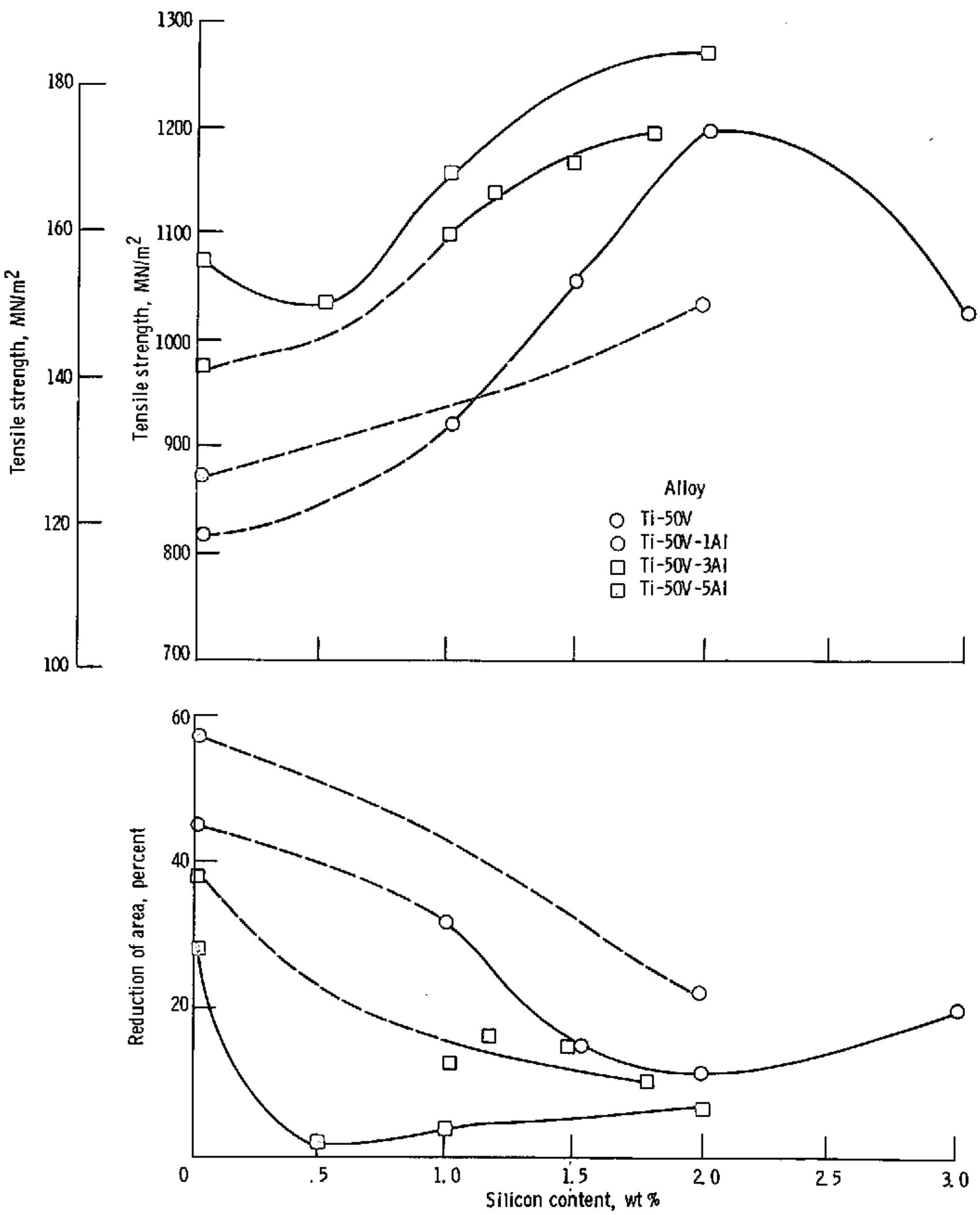


Figure 5. - Effect of silicon content on tensile properties at 23° C of titanium-vanadium-aluminum alloys.

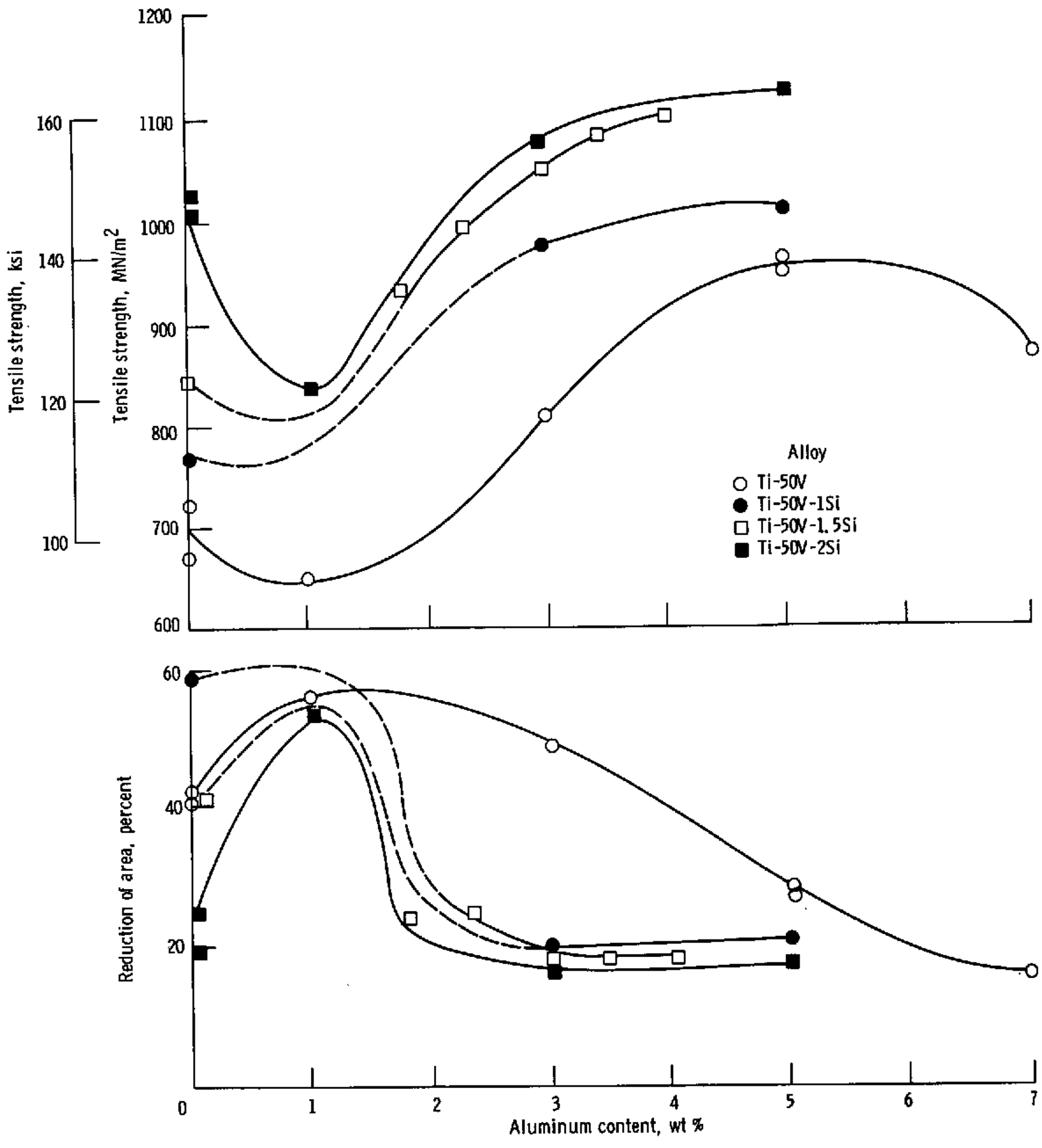


Figure 6. - Effect of aluminum content on tensile properties at 500° C of titanium-vanadium-silicon alloys.

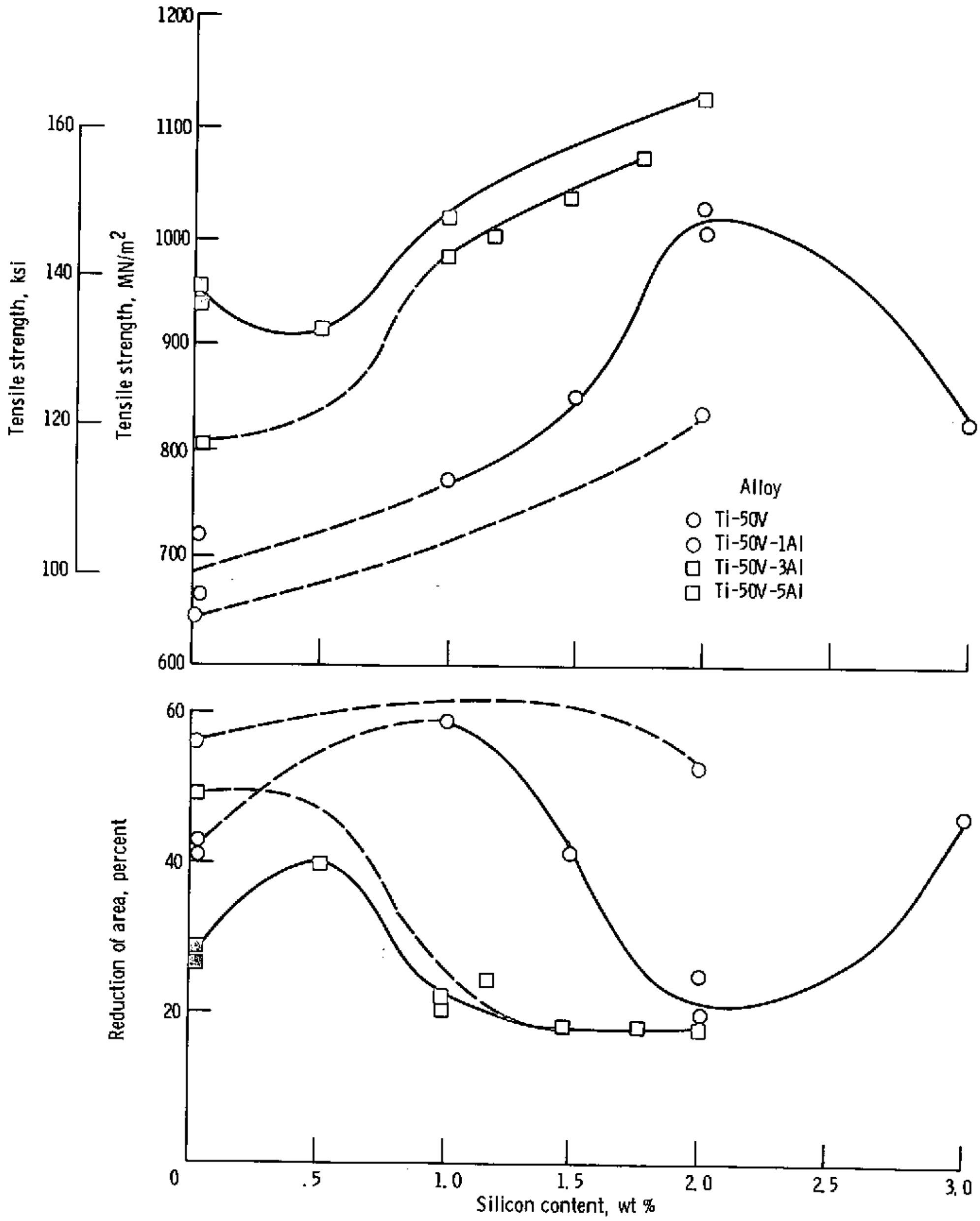


Figure 7. - Effect of silicon content on tensile properties at 500° C of titanium-vanadium-aluminum alloys.

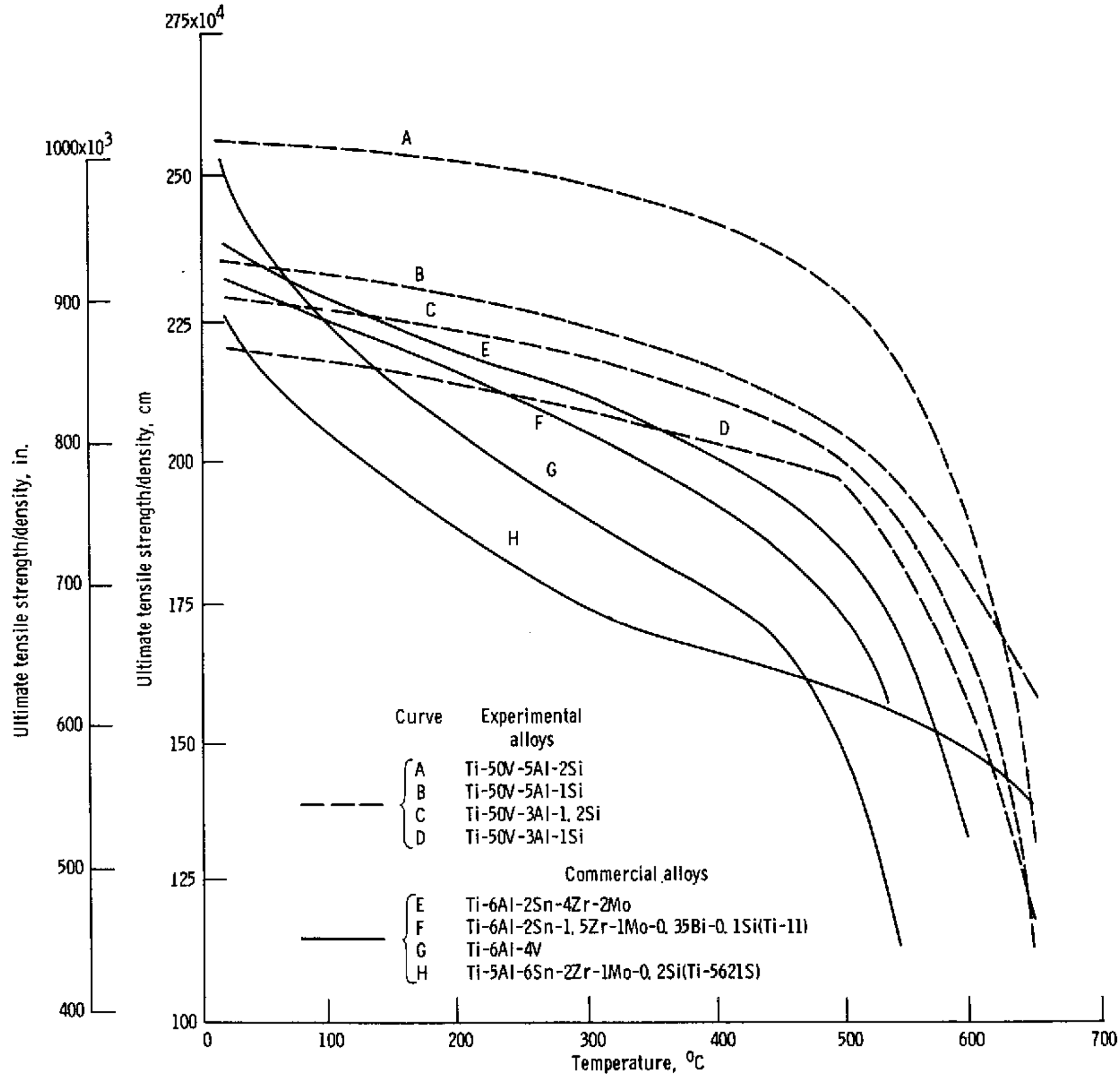


Figure 8. - Comparison of specific tensile strengths of experimental titanium alloys with several commercial (refs. 10 and 11) titanium alloys.

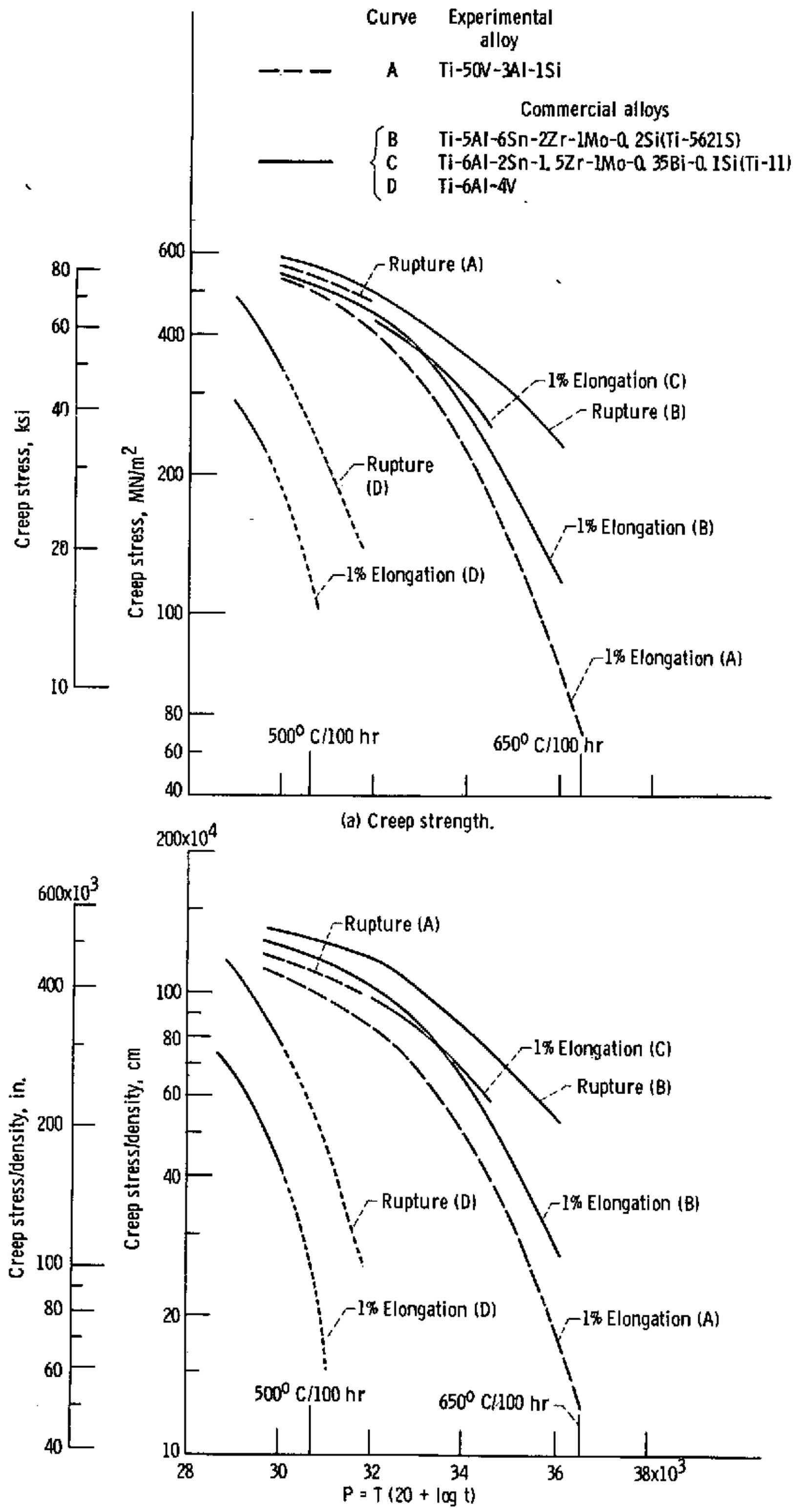


Figure 9. - 100-Hour creep rupture and 1 percent creep elongation curves for experimental and commercial (refs. 10 and 11) titanium alloys.

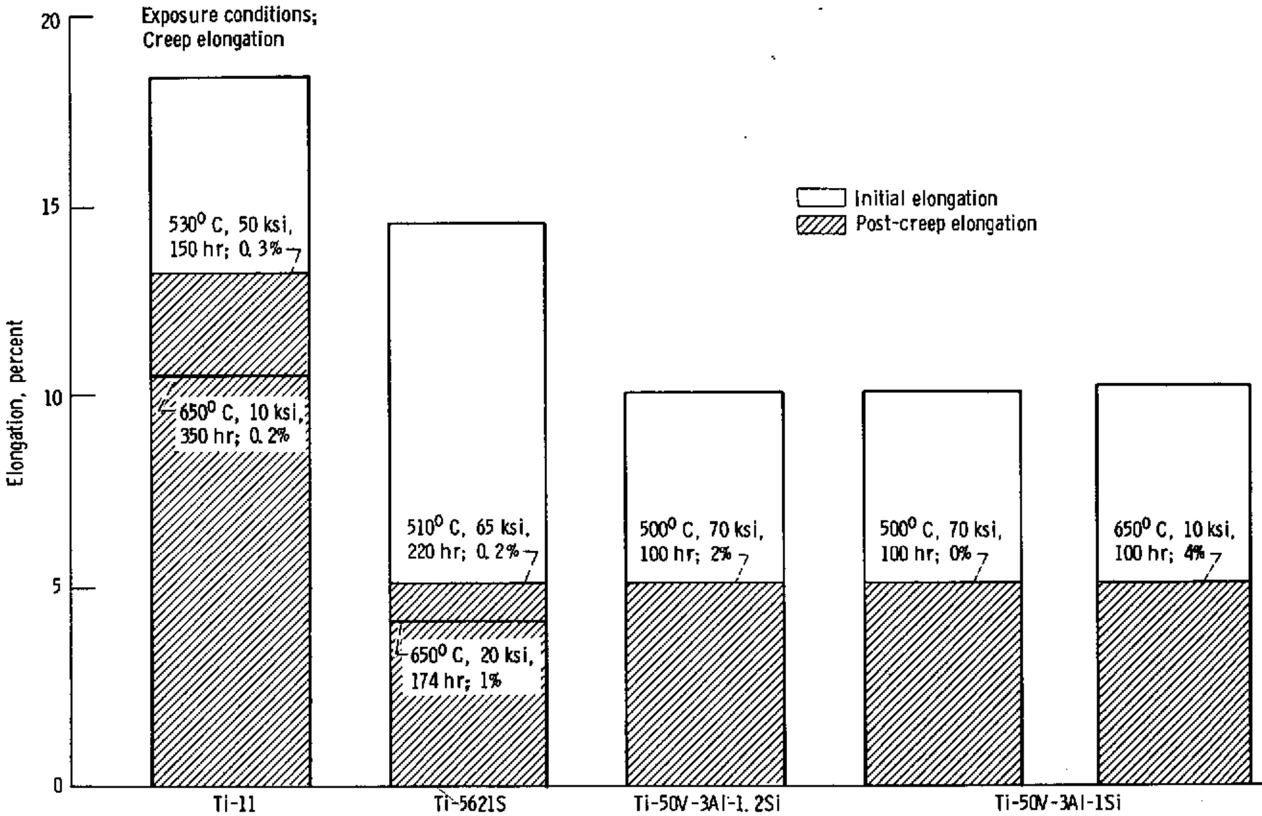


Figure 10. - Effect of creep exposure on room-temperature tensile ductility of experimental and commercial (ref. 10) titanium alloys. Ti-11 denotes Ti-6Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si; Ti-5261S denotes Ti-5Al-6Sn-2Zr-1Mo-0.2Si.

NASA-Langley, 1975 E-8187