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Mechanical Behavior of Aged Uranium-3/4 Weight Percent Titanium Alloy

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by

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ABSTRACT

The mechanical behavior of the uranium-3/4 weight percent titanium alloy in the aged condition has been characterized by tension, notched tension, and compression tests. These tests were made over a temperature range of -196°C to 80°C, at strain rates from .001 s^{-1} to 2000 s^{-1}. Metallography on selected samples using optical and scanning electron microscopes was used to identify fracture modes. Compression and smooth tensile tests showed a linear decrease in yield strength with increasing temperature, and for tensile tests, a linear decrease in ultimate tensile strength with increasing temperature. The corresponding tensile ductility was relatively constant at temperatures above 0°C, then decreased rapidly with decreasing temperature. Notched tensile tests showed a ductile-to-brittle transition at about -40°C. SEM photographs showed a mixture of ductile-dimple fracture and brittle cleavage areas in all notched tensile sample fracture surfaces. Fracture surfaces on smooth tensile test samples showed a ductile-dimple structure at 80°C, a primarily ductile-dimple structure with some long narrow cleavage facets at 24°C, and a mostly cleavage structure at -54°C. The mechanical threshold stress model was fit to yield stress data and the parameters for an equation describing yield stress as a function of temperature and strain rate were determined.

Introduction

The uranium-3/4 weight percent titanium alloy is useful in applications requiring higher strength properties than unalloyed uranium. It is generally used in the quenched and aged condition, with maximum strength (and minimum ductility) achieved with aging at 450°C, and a good compromise between strength increase and ductility decrease with aging at 385°C (1-3). This report describes mechanical measurements of this alloy in the quenched and aged condition where aging was done at 385°C for 4 and 8 hours, with tests performed at a series of temperatures between -196°C and 80°C.

Material

The material was obtained from the Martin-Marietta Y-12 plant, Oak Ridge, TN, in the form of a casting. The casting had been immersion quenched and aged at 385°C for 4 hours. The chemistry of the casting was not available except for a reported internal hydrogen content of 0.44 weight parts per million. The microstructure in this condition consisted of a supersaturated alpha phase martensite, with very fine coherent precipitate particles. A typical as-received microstructure is shown in Fig. 1. Some tensile specimens were given an additional 4 hour aging in vacuum at 385°C.

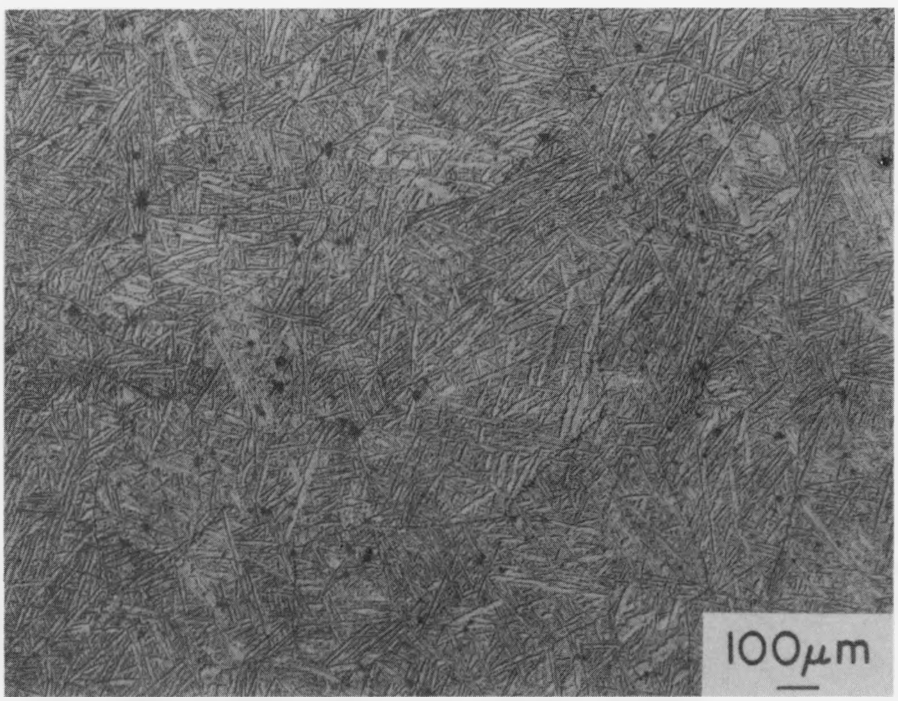

Fig. 1. As received U-3/4Ti alloy microstructure. Material has been water-quenched, then aged at 385 °C for 4 hours.

Tests

Smooth tension, notched tension, and compression tests were performed, using a screw-driven universal testing machine (Tinius Olsen Lo-Cap, 133 kN [30 000 pound] capacity) equipped with environmental chambers. Tests were generally conducted either in vacuum or in an inert atmosphere of helium or nitrogen, except for several tests where dry or water-saturated air was used for comparison. Compression tests employed a subpress for accurate specimen alignment, and used an unbonded strain gage extensometer to record sample strain. High strain rate tests were performed using a split Hopkinson pressure bar apparatus. Extension measurements during tension tests were made with an optical extensometer with a resolution of 0.015mm (0.0006 inches).

Samples

The smooth tension samples were machined to the dimensions shown in Fig. 2, producing a gage length of 18mm (0.7 inches) and a gage diameter of 2.3mm (0.09 inches). Most of these samples were electropolished before use except for a few that were hand-polished with 600 grit metallographic paper. No significant difference in results was found between samples electropolished and those hand-polished. However, the scatter in both the strength and elongation measurements was less than previously experienced with as-machined samples. The electropolish bath was a mixture of CrO_3 and acetic acid; polishing conditions were 35 volts at 25°C.

Notched tension samples used the same overall specimen shape except that a uniform shoulder-to-shoulder diameter of 3.18 mm (0.125 inches) was used, with a central 60 degree notch having a tip radius of 0.025 mm (0.001 inch), and a reduced section diameter of 2.3 mm (0.090 inches), as shown in Fig. 3. These specimens were not electropolished before use.

Compression specimens were cut from the 3.18 mm diameter ends of the smooth tension specimens with a low speed diamond saw and the ends lapped flat and parallel by hand, with the aid of a polishing jig. Finished dimensions were approximately 3.8 mm

Round Tensile Specimen

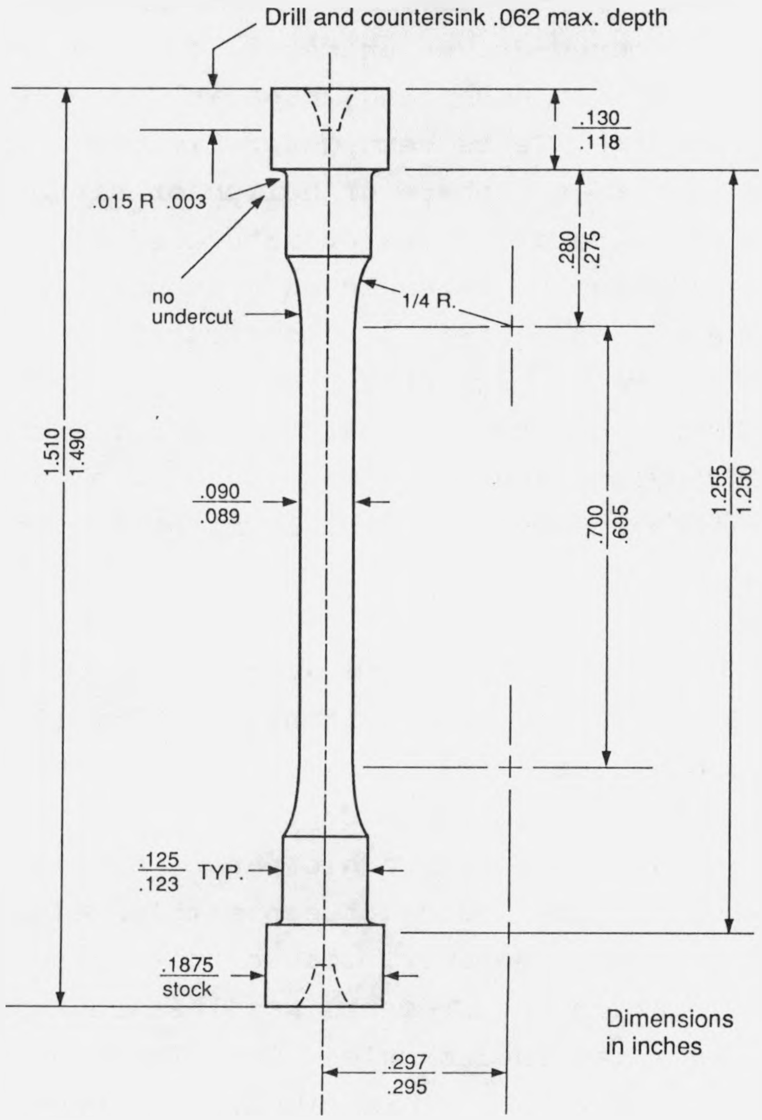

Fig. 2. Round tensile specimen machining specifications. Samples given a hand or electropolish after machining and before testing.

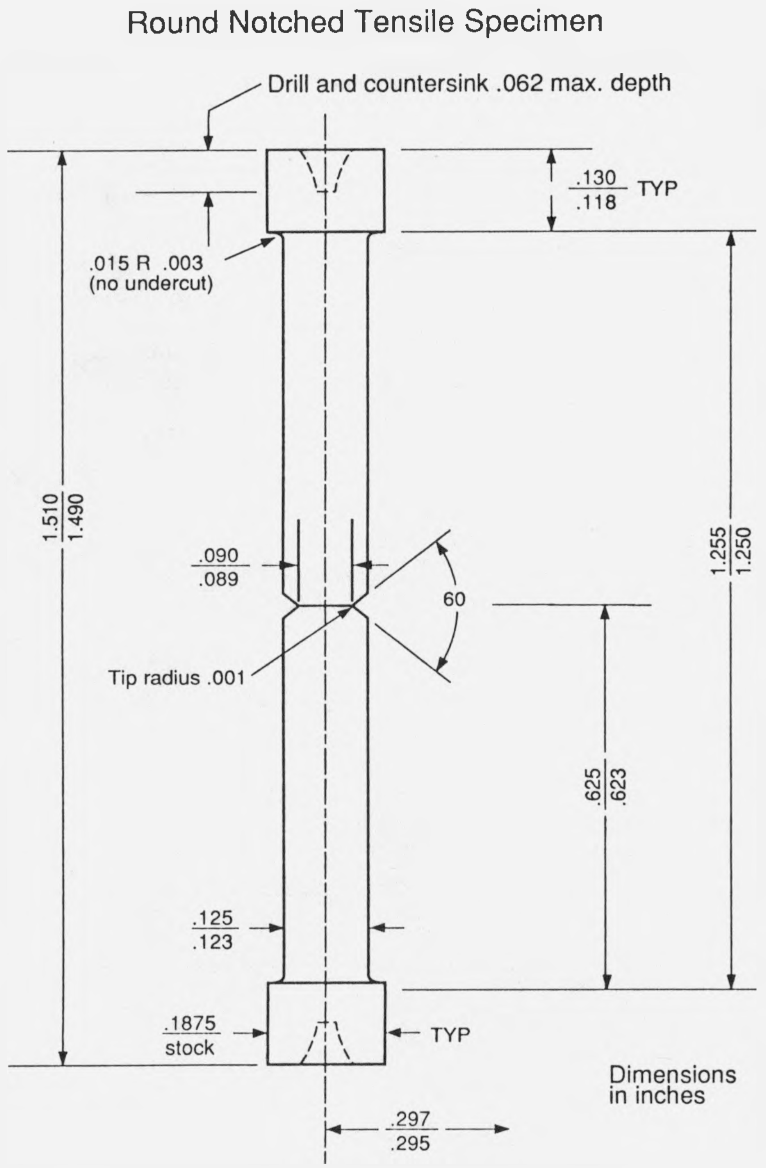

Fig. 3. Round notched tensile specimen machining specifications. Samples to be tested in the as-machined condition.

TABLE 1

Tensile Properties of U-3/4Ti Alloy Aged 4 Hours at 385°C

Test Temp (°C)	Strain Rate s^{-1}	Yield Strength MPa(KSI)	U.T.S. MPa(KSI)	Uniform elong.	Total elong.	Reduction in area %	Comments	*
80	0.001	835(121)	1325(192)	0.14	0.15	40	electropol	1
80	.0016	971(141)	1342(195)	.13	.16	34	hand pol	2
80	.0017	939(136)	1431(208)	.17	.20	27	electropol	2
80	.60	835(121)	1299(188)	.12	.13	41	electropol	1
24	.001	875(127)	1408(204)	.18	.19	26	"	1
24	.001	840(122)	1465(212)	.21	.23	32	"	1
24	.001	840(122)	-	-	-	-	"	1
24	.0014	840(122)	1508(219)	.12	.13	27	elect- air	2
24	.0015	984(143)	1572(228)	.13	.19	24	hand pol-"	2
24	.0015	980(142)	1392(202)	.14	.16	32	electropol	1
24	.025	1061(154)	1502(218)	.14	.19	34	hand pol "	2
24	.243	984(143)	1508(218)	.11	.14	28	" "	2
24	.5	890(129)	1414(205)	.12	.14	40	electropol	1
10	.001	1050(152)	1546(224)	.14	.15	7	"	2
-10	.0012	1022(148)	1623(235)	.16	.18	14	"	2
-10	.005	960(139)	1572(228)	.15	.16	11	"	2
-54	.001	1020(148)	1592(231)	.11	.11	9	"	1
-54	.0012	1061(154)	1629(236)	.08	.08	6	hand pol	2
-54	.0013	971(141)	1687(245)	.13	.13	9	electropol	2
-54	.60	970(141)	1580(229)	.14	.15	20	"	1

* (1) First batch of samples
(2) Second batch of samples

TABLE 2

Tensile Properties of U-3/4Ti Alloy Aged 8 Hours at 385°C

Test Temp (°C)	Strain Rate s^{-1}	0.2 % Yield Strength MPa(KSI)	U.T.S. MPa(KSI)	Uniform elong.	Total elong.	Reduction in Area %
80	.0016	980(142)	1427(207)	.12	.13	29
24	.009	981(142)	1401(203)	.09	.10	24
-54	.001	-	1490(216)	.07	.07	6
-54	.6	-	1452(211)	.02	.02	4
-54	.6	1100(161)	1478(214)	.05	.05	7

(0.150 inches) long and 3.18 mm (0.125 inches) in diameter. The samples were tested in the as-lapped condition. Other compression samples were slightly larger, with lengths of 5.6 mm (0.22 inches) and diameters of 4.8 mm (0.19 inches).

Results

The results of testing 20 smooth tensile samples of the as-received (aged 4 hours at 385°C) material are listed in Table 1. Most of the tests were performed at a nominal strain rate of 0.001 per second. Plots of these data are shown in the next four figures. Figure 4 shows a plot of 0.2 percent offset yield strength and ultimate tensile strength versus temperature. A linear regression analysis of the ultimate tensile strength (U.T.S.) data produced the equation shown and the corresponding line, ignoring the effect of strain rate.

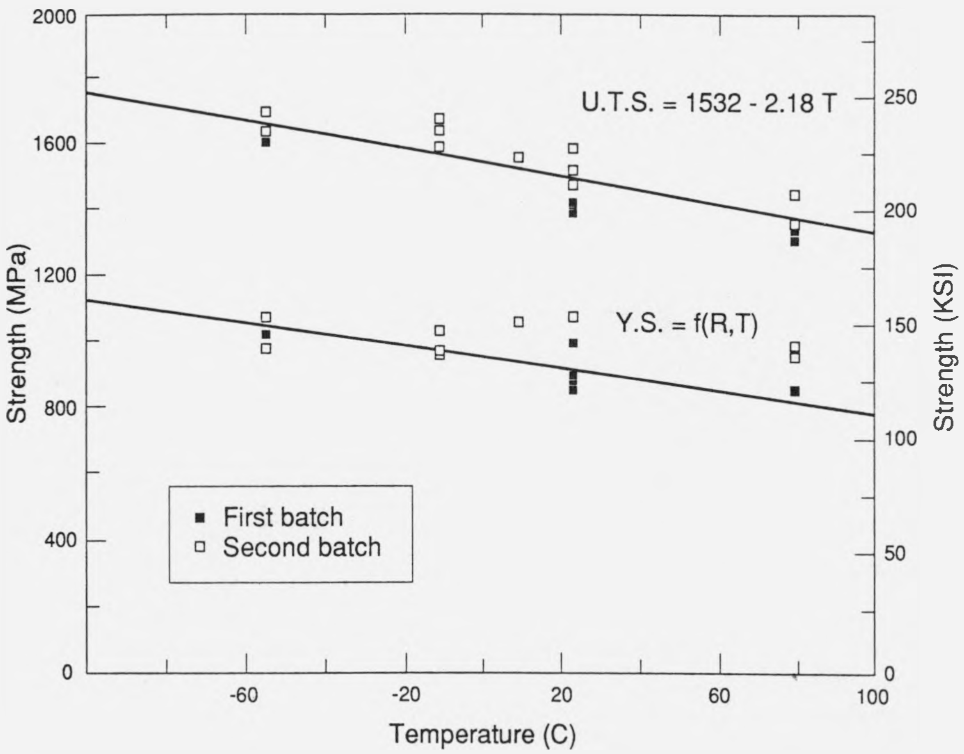

Fig. 4. Tensile tests of U-3/4Ti alloy that was aged 4 hours at 385°C. Strain rates from 0.001 to 0.6 s^{-1}. Ultimate tensile strength (U.T.S.) curve from linear regression fit. Yield strength (Y.S.) from the MTS model. (See text and Appendix A)

The line shown for the yield strength (Y.S.) was derived from the application of the mechanical threshold stress model (MTS) where yield stress is a function of strain rate and test temperature. The model is discussed in Appendix A.

Two sets of samples were used (first and second batch), the second batch being machined several months after the first set. Figure 5 shows a plot of the corresponding uniform elongations and Fig. 6 shows a similar plot of total elongations. Figure 7 shows a plot of corresponding post-test reduction-in-area measurements as well as four measurements from samples aged a total of 8 hours at 385°C. Figure 8 is a composite plot of stress versus strain for several smooth tension tests of samples aged 4 hours at 385°C and tested at 80°C at different strain rates.

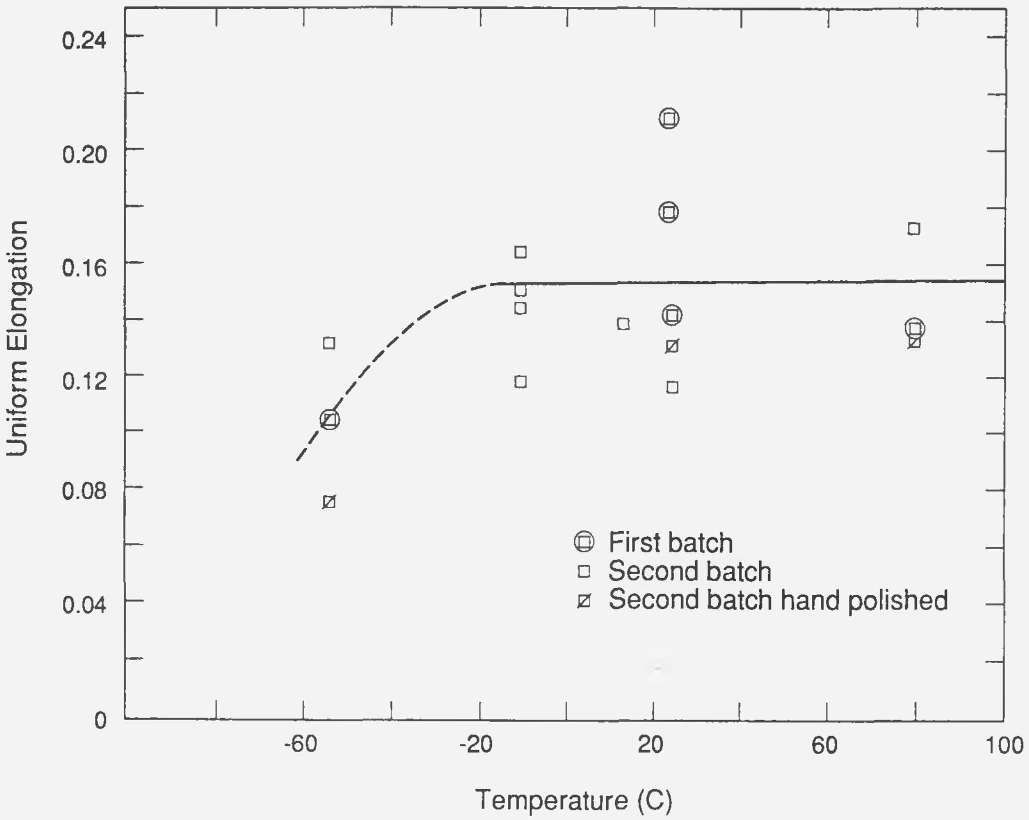

Fig. 5. Tensile uniform elongations of U-3/4Ti alloy aged 4 hours at 385 °C, at a nominal strain rate of 0.001 s^{-1}.

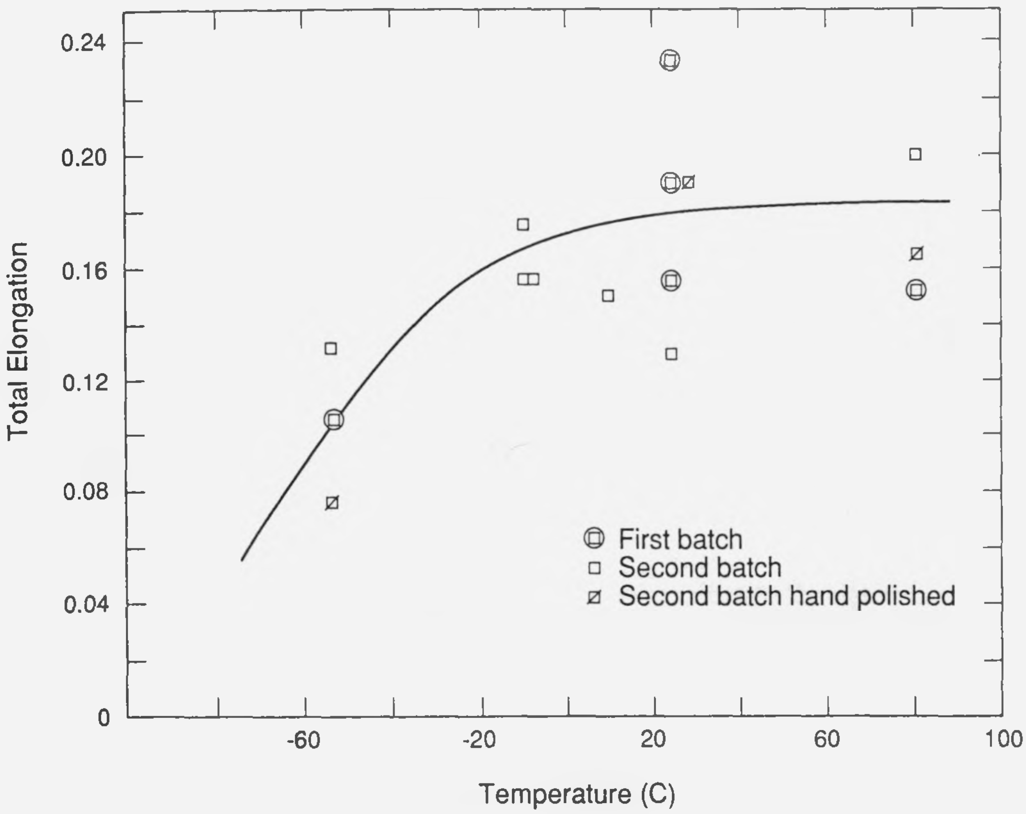

Fig. 6. Tensile total elongations of U-3/4Ti alloy aged 4 hours at 385°C, at a nominal strain rate of 0.001 s^{-1}.

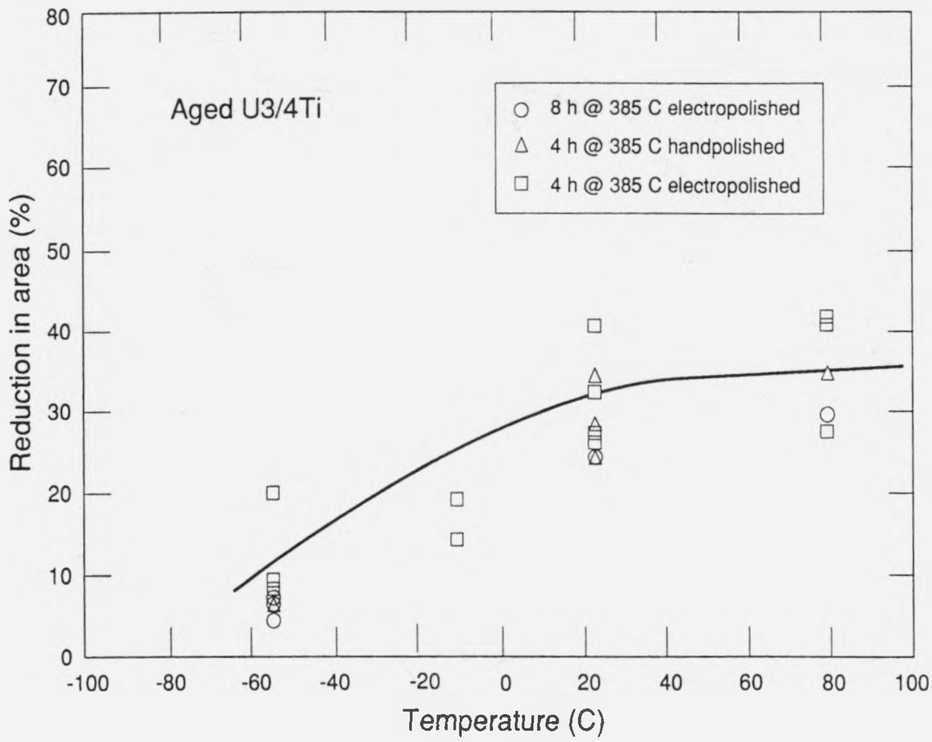

Fig. 7. Tensile reductions-in-area of U-3/4Ti alloy aged at 385°C, tested at a nominal rate of 0.001 s^{-1}.

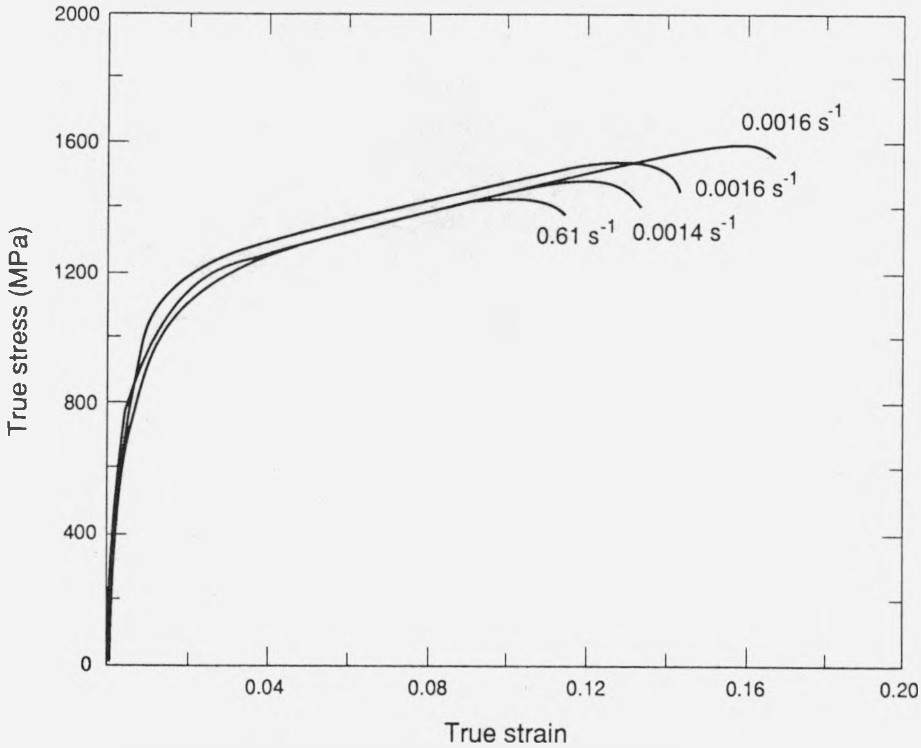

Fig. 8. Tensile test results of U-3/4Ti alloy aged 4 hours at 385°C. Test rates in units of s^{-1} indicated on figure, for samples tested at 80°C.

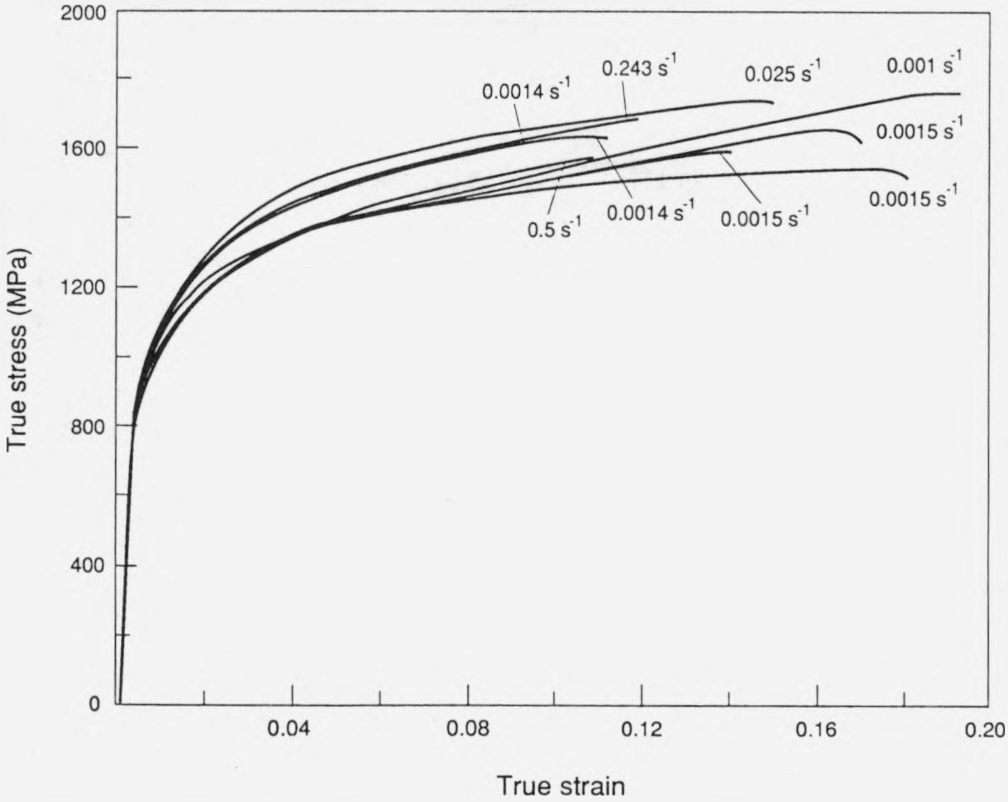

Fig. 9. Tensile test results of U-3/4Ti alloy aged 4 hours at 385°C. Test rates in units of s^{-1} indicated on the figure, for samples tested at 24°C.

Figure 9 is a similar plot but for samples tested at 24°C, and Fig. 10 is a similar plot for samples tested at -54°C. Figure 11 shows plots of smooth tension tests at a nominal strain rate of 0.001 per second and at several test temperatures for samples for batch 1 (Fig. 11a) and batch 2 (Fig. 11b).

Table 2 lists the results of smooth tension tests of 5 samples that were aged a total of 8 hours at 385°C. The 0.2 percent offset yield strengths and ultimate tensile strengths are plotted versus temperature in Fig. 12. Corresponding uniform and total elongation values are plotted in Fig. 13a. Figure 13b is a plot of compression test results from an aging study for this material which had been aged for various times at 400°C.

Figure 14 is a plot of uniform elongation measured on smooth tensile test specimens versus the corresponding reduction-in-area measurements. The curve labeled "Calculated RA vs. UE" is the reduction-in-area computed at maximum uniform elongation, assuming constant volume within the gage section. Points that lie to the right of the curve represent tests that exhibit some

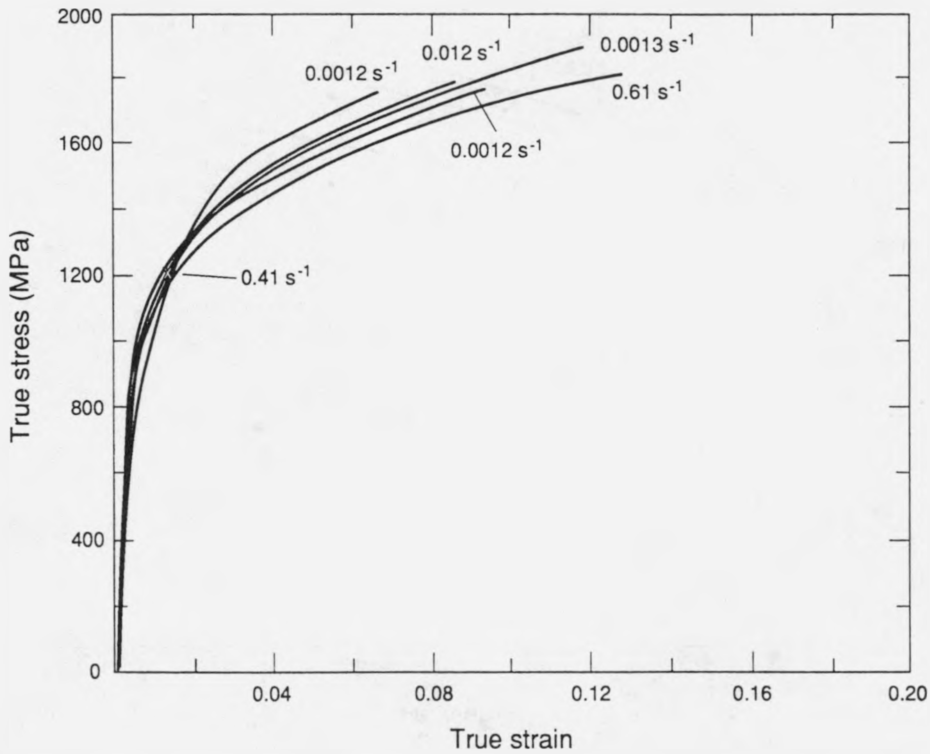

Fig. 10. Tensile test results of U-3/4Ti alloy aged 4 hours at 385°C. Test rates in units of s^{-1} indicated on the figure, for samples tested at -54°C.

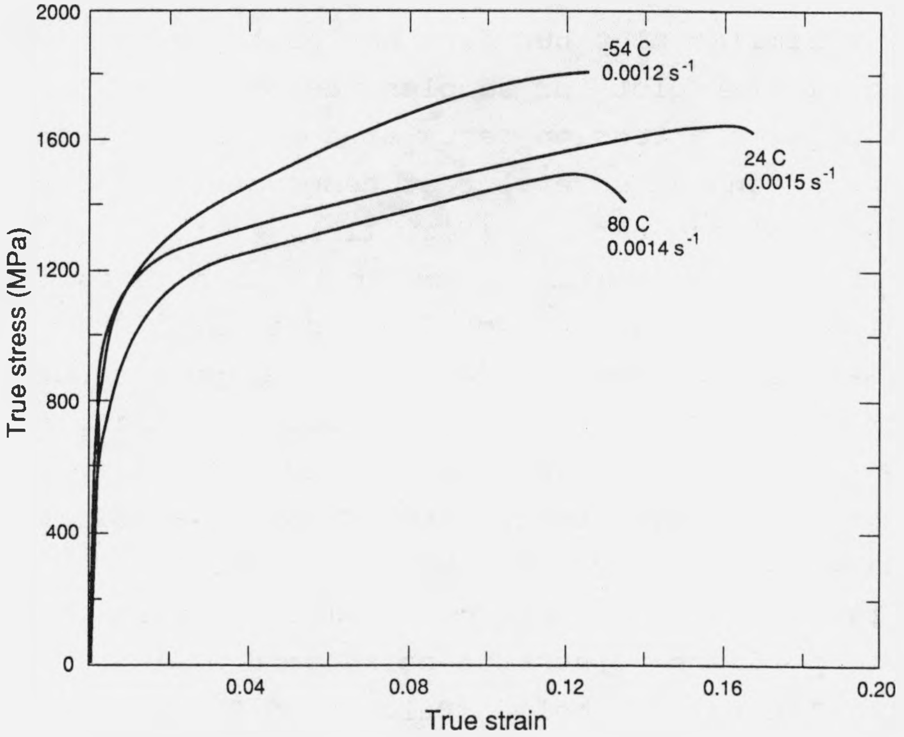

Fig. 11a. Tensile test results from the first batch of samples of U-3/4Ti alloy aged 4 hours at 385°C. Test temperatures in °C and test rates in units of s^{-1} shown on figure.

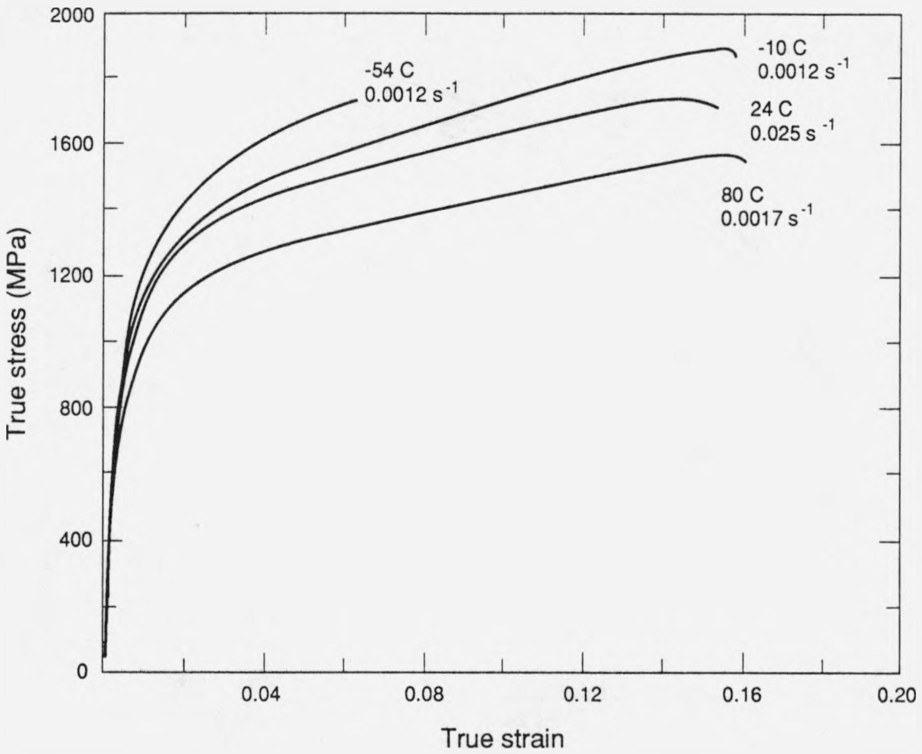

Fig. 11b. Tensile test results from the second batch of samples of U-3/4Ti alloy aged 4 hours at 385°C. Test temperatures in °C and test rates in units of s^{-1} shown on figure.

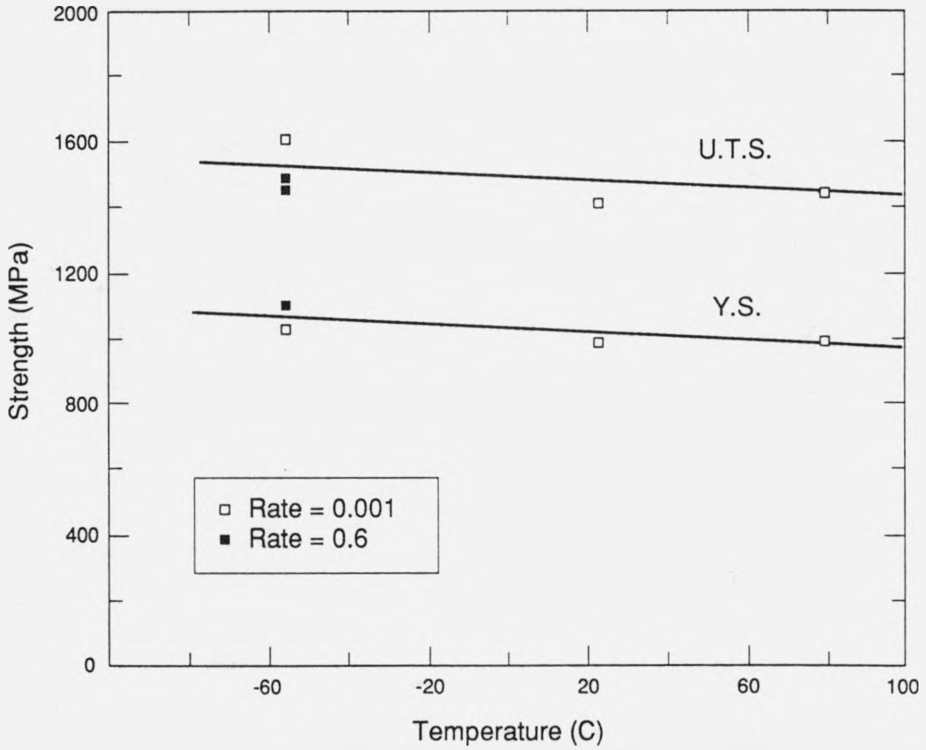

Fig. 12. Tensile strengths of U-3/4Ti alloy samples aged a total of 8 hours at 385°C, at strain rates of 0.001 s^{-1} and 0.6 s^{-1}. Upper curve is for ultimate tensile strengths and the lower curve is for 0.2% offset yield strengths.

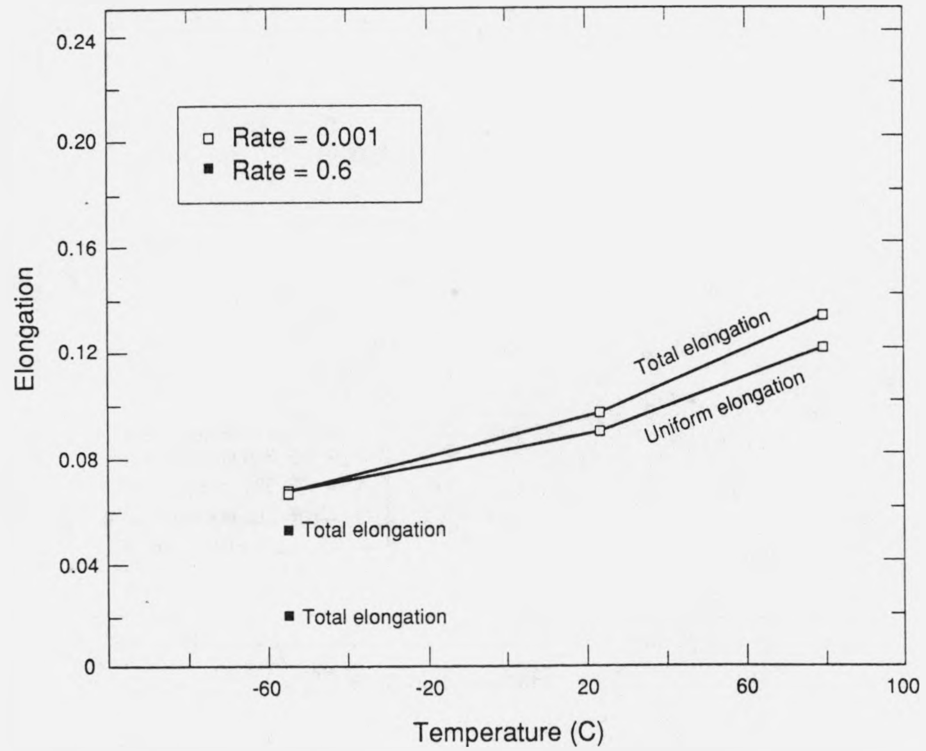

Fig. 13a. Total and uniform elongations of U-3/4Ti alloy samples aged a total of 8 hours at 385 °C, at strain rates of 0.001 and 0.6 s^{-1}.

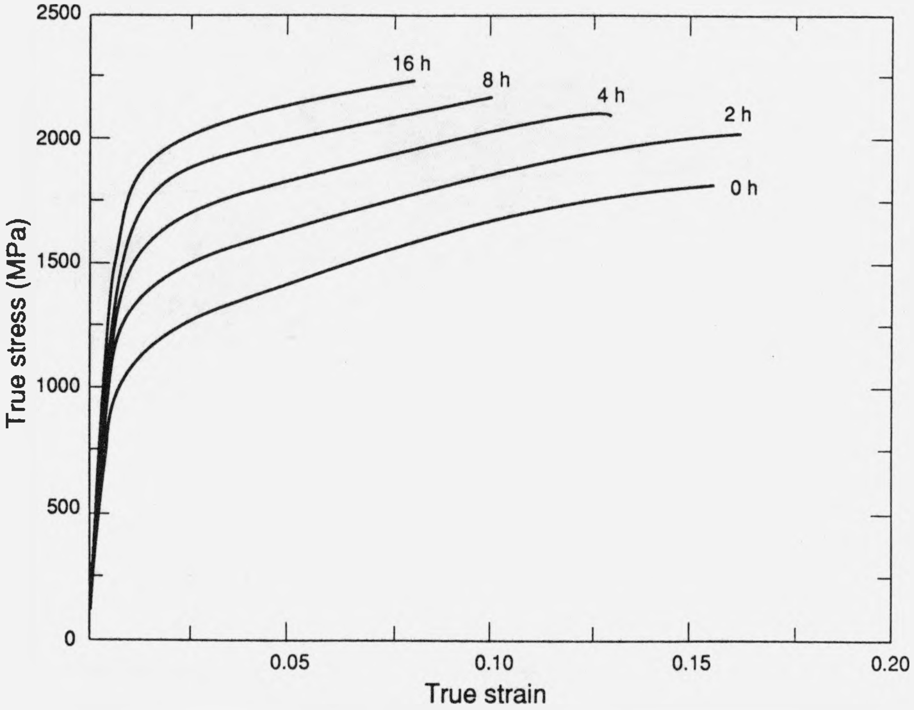

Fig. 13b. Compressive stress-strain curves for the U-3/4Ti alloy quenched and aged at 400°C for various times.

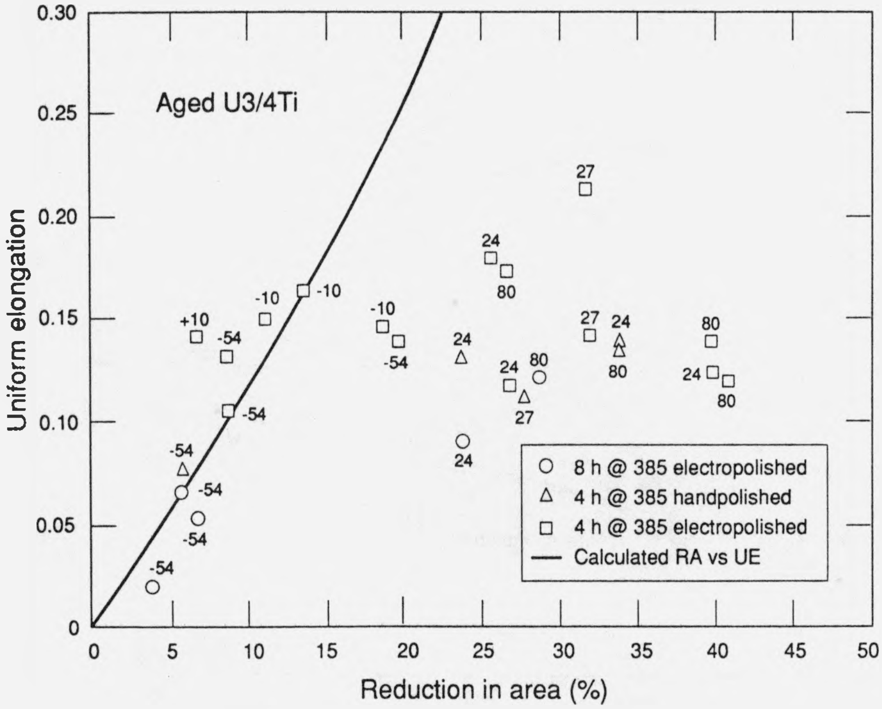

Fig. 14. Uniform elongation versus corresponding reduction-in-area measurements for several sample conditions. Test temperatures in °C indicated for each test. Tests to the right of the curve have local necking deformations.

degree of local necking beyond the strain at the ultimate tensile strength (corresponding to maximum uniform strain), while points on the curve or to the left of it show fracture before local necking occurs.

The results of the notched tensile tests are compiled in Table 3. All samples were tested in the as-received, aged condition (aged 4 hours at 385°C). Two nominal loading rates were used, a relatively low rate of approximately 385 MPa per second, and the testing machine maximum rate of approximately 12 000 MPa per second. The optical extensometer was used to measure the change in the width of the notch at fracture. Fracture in all cases appeared to occur at maximum load.

Figure 15 is a plot of maximum stress measured in the notched tensile tests versus test temperature. Lines representing the average values of smooth tensile test yield stresses and ultimate

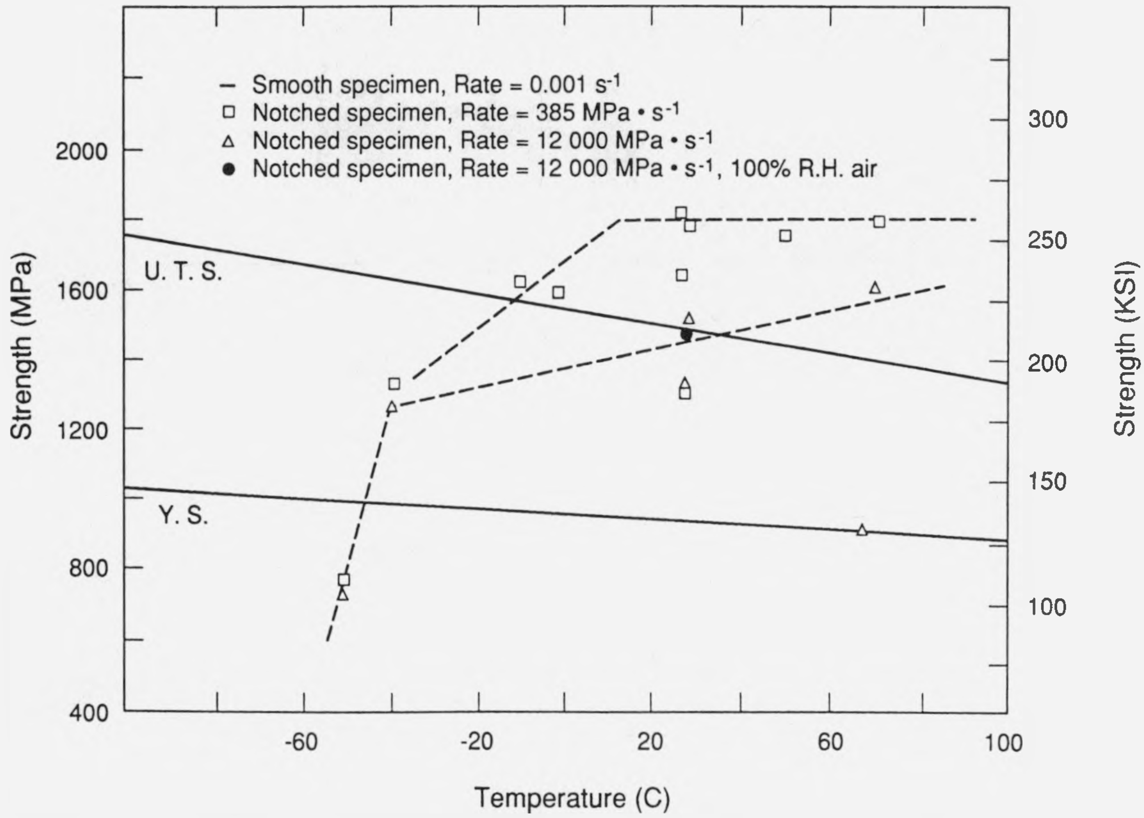

Fig. 15. Notched tensile test maximum stress measurements for several loading rates and test atmospheres. Smooth tensile test results curves of ultimate tensile strength (U.T.S.) and 0.2% offset yield strengths (Y.S.) shown for comparison.

TABLE 3

Notched Tensile Tests of U-3/4Ti Alloy Aged 4 Hours at 385°C

Temperature (°C)	Loading Rate $MPa*s^{-1}$	Atmosphere	Maximum Stress MPa	Maximum Notch Width Change, inches
70	391	nitrogen	1776	.0052
70	41	"	1546	-
50	437	"	1738	.0027
29	455	vacuum	1776	.0059
28	365	"	1802	-
27	398	"	1275	.0028
27	407	"	1625	.0026
0	388	helium	1578	.0006
-10	401	"	1617	-
-36	397	"	1316	.0026
-50	365	"	767	-
70	12700	nitrogen	1587	.0010
70	9300	"	907	.0011
28	11800	vacuum	1498	.0009
28	12500	wet air	1457	.0014
24	2200	vacuum	1319	-
-35	11900	helium	1255	-
-50	9700	"	734	.0004

tensile stresses are shown for comparison. Figure 16 is a plot of notched tensile test notch width change ("elongation") versus test temperature. Figure 17 is a plot of notch yield ratios versus test temperature, where the notch yield ratio is the ratio

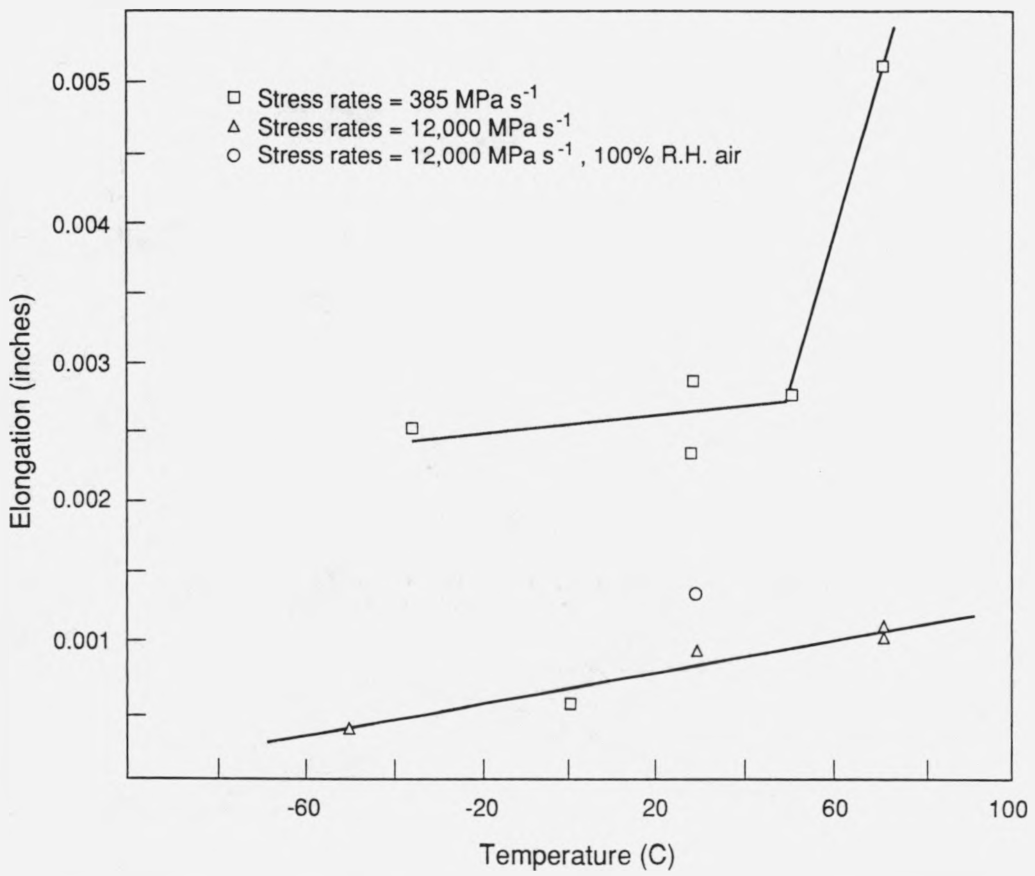

Fig. 16, Change in notch width for notched tensile tests for several loading rates and test atmospheres.

of observed notched tensile test maximum stress to the smooth tensile test 0.2 percent offset yield stress at the same temperature.

The results of the twelve compression tests are shown in the next two figures. Figure 18 is a plot of true stress versus true strain for tests at 24°C with different strain rates. Figure 19 is a plot of true stress versus true strain for tests at low strain rates and different temperatures. Table 4 summarizes compression yield strength measurements on samples made from

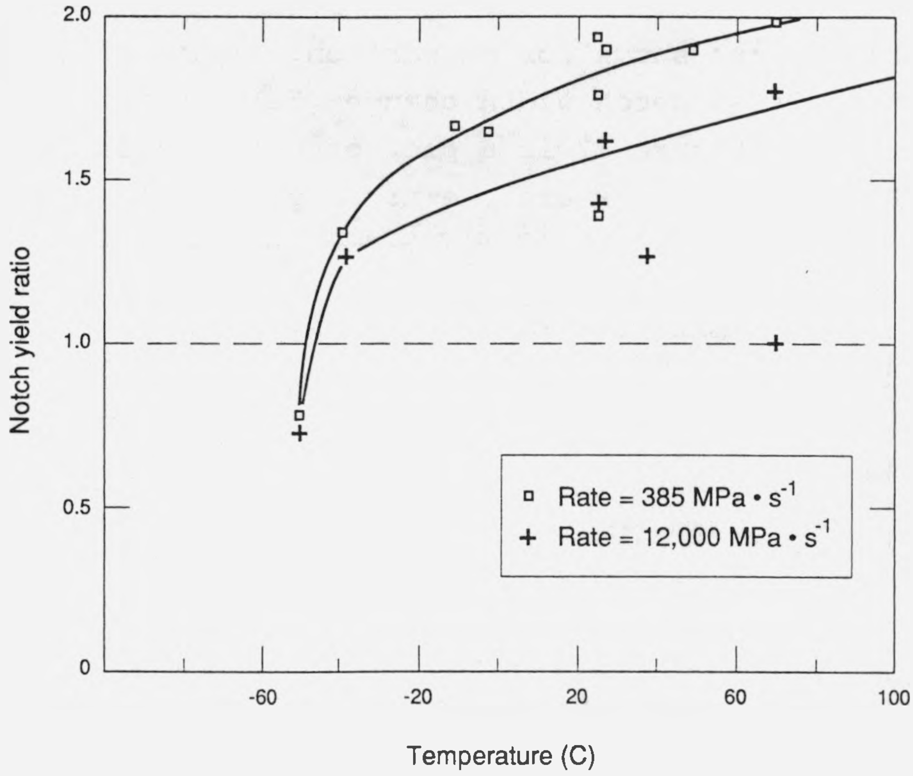

Fig. 17. Calculated notch yield ratios for U-3/4Ti alloy aged 4 hours at 385°C, from notched and smooth tensile test results.

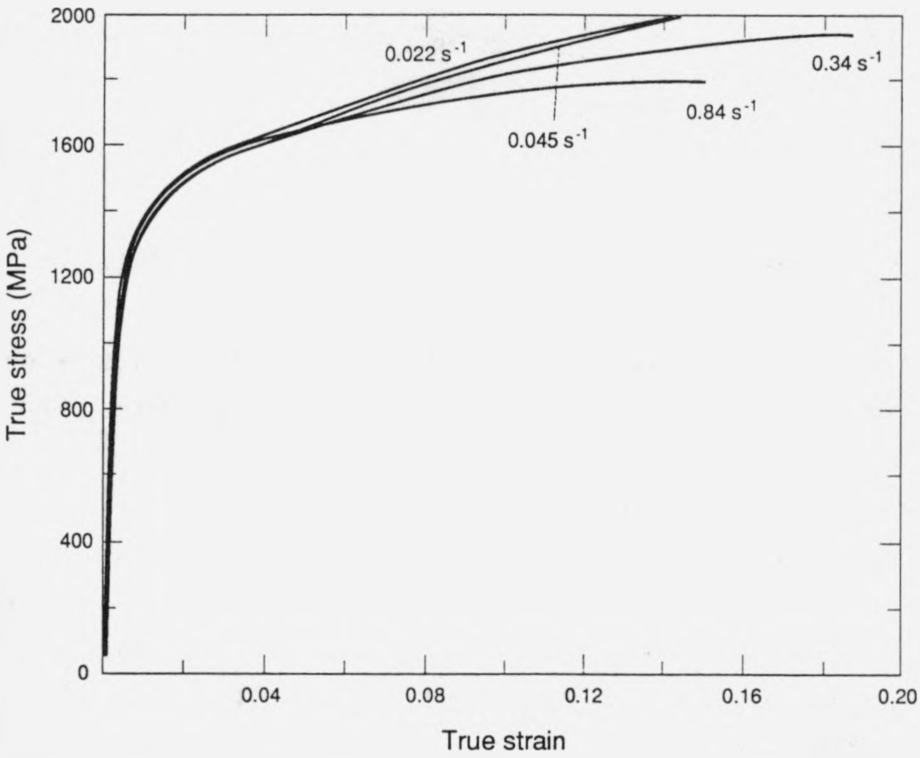

Fig. 18. Compression test results at a test temperature of 24°C and several strain rates, for U-3/4Ti alloy aged 4 hours at 385°C.

tensile specimen ends, on samples with larger dimensions machined from the same stock, and on samples with a length-to-diameter ratio of 0.5, tested in the split Hopkinson pressure bar apparatus.

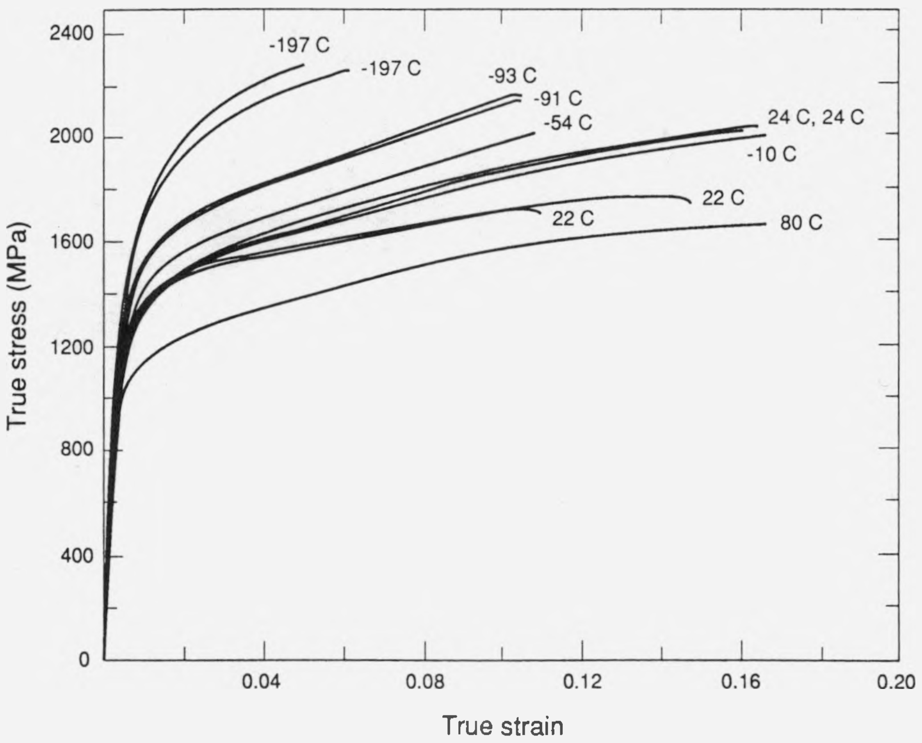

Fig. 19. Compression test results at various temperatures for the U-3/4Ti alloy aged 4 hours at 385°C. Nominal strain rates were 0.001 s^{-1}.

Characterization of the fracture surfaces of representative samples of smooth tensile tests and notched tensile tests was performed using scanning electron microscopy (SEM). All SEM micrographs were taken at a magnification of 300X, except for one micrograph of each sample showing the entire fracture surface, which was taken at a magnification of 30X. Figures 20 through 23 show the fracture surfaces of smooth tensile test samples tested at 80°C, 24°C, and -54°C, at a nominal strain rate of 0.001 per

TABLE 4

Compression Yield Tests for U-3/4Ti Alloy Aged 4 Hours at 385°C

Temperature °C	Strain Rate s^{-1}	Yield Strength MPa(KSI)	Condition
80	.0011	1026(149)	Tensile bar ends,
24	.0022	1179(171)	0.2 % offset
24	.022	1083(157)	"
24	.045	1269(184)	"
24	.34	1205(175)	"
24	.84	1205(175)	"
-10	.0012	1179(171)	"
-54	.0011	1179(171)	"
22	.0006	1141(165)	Compression specimens
22	.001	1207(175)	0.2 % offset
22	.35	1223(177)	"
22	.40	1252(182)	"
-91	.0004	1475(214)	"
-93	.0004	1404(204)	"
-197	.0002	1605(239)	"
-197	.001	1650(239)	"
22	.001	1328(193)	Back extrapolated
22	.0015	1365(198)	about .01 offset
22	.8	1432(208)	"
22	.8	1422(206)	"
22	2000	1519(220)	Hopkinson bar "
22	2000	1503(218)	" "
22	2000	1495(217)	" "
22	1500	1566(227)	" "
-91	.0015	1625(236)	Back extrapolated
-93	.0015	1661(241)	"
-196	.0015	1850(268)	"
-197	.0015	1940(281)	"

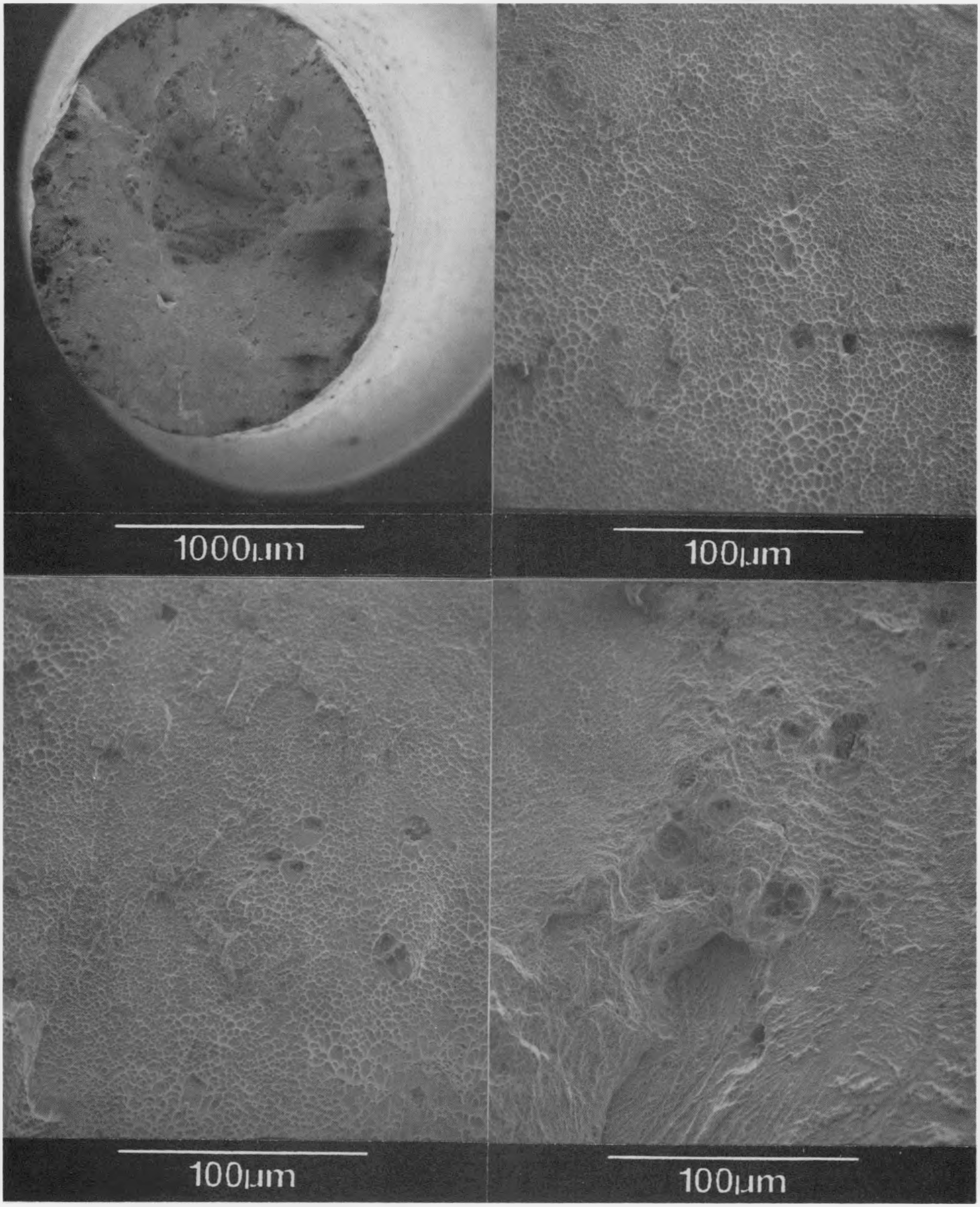

Fig. 20. SEM photographs of a smooth tensile test fracture surface of a sample tested at 80 C, at a strain rate of 0.001 s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

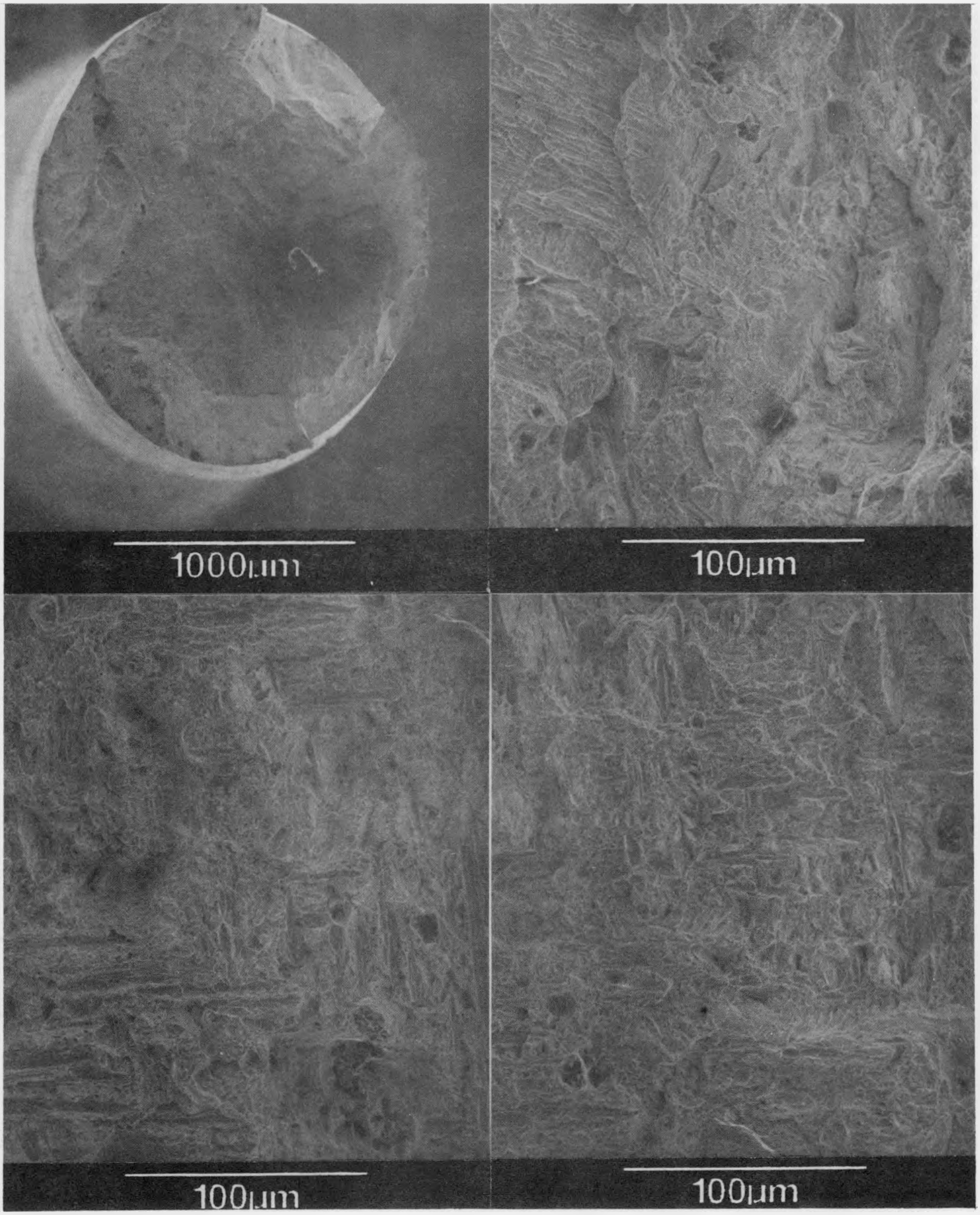

Fig. 21. SEM photographs of a smooth tensile test fracture surface of a sample tested at 24 C, at a strain rate of 0.001 s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

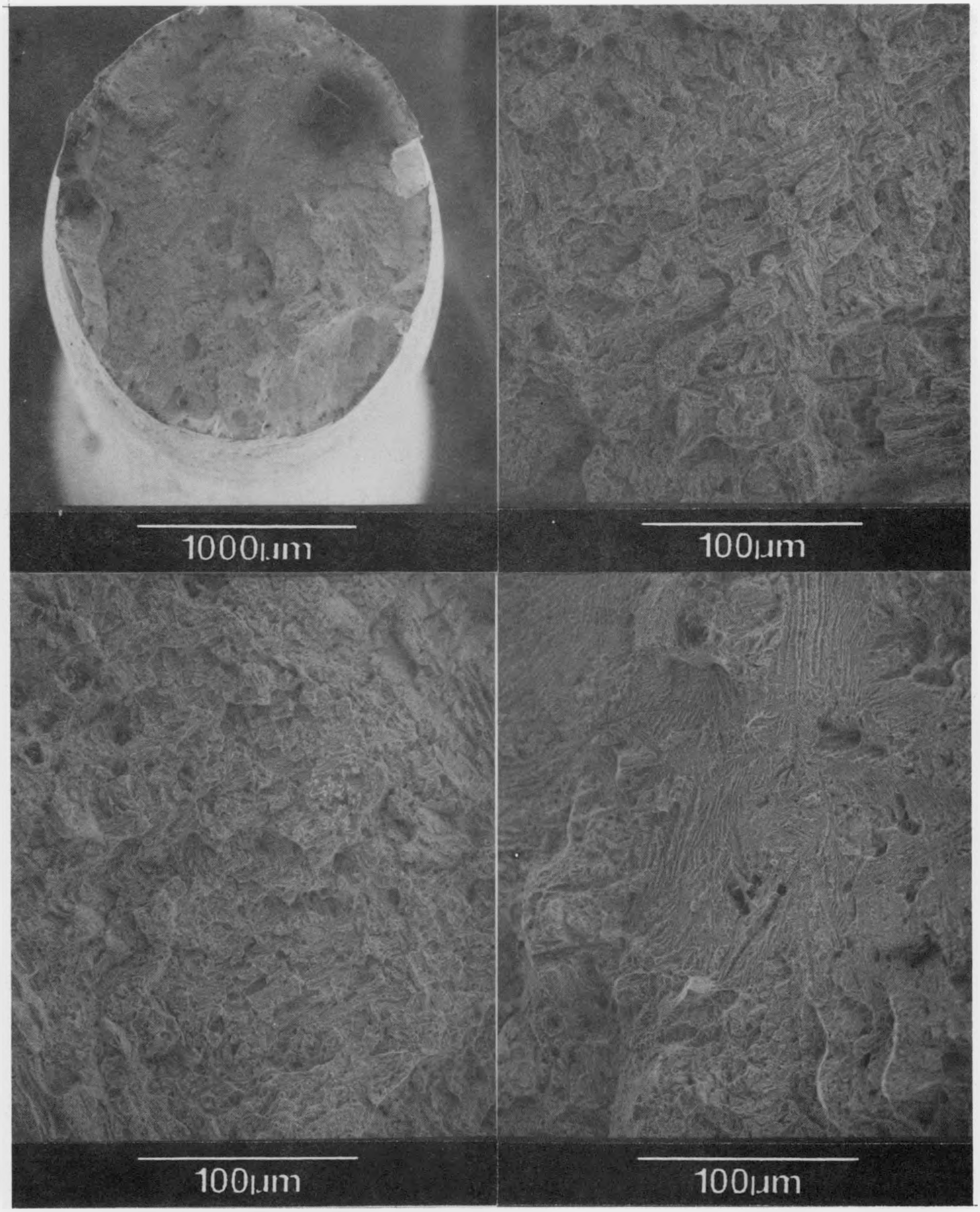

Fig. 22. SEM photographs of another smooth tensile test fracture surface of a sample tested at 24 C, at a strain rate of 0.001 s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

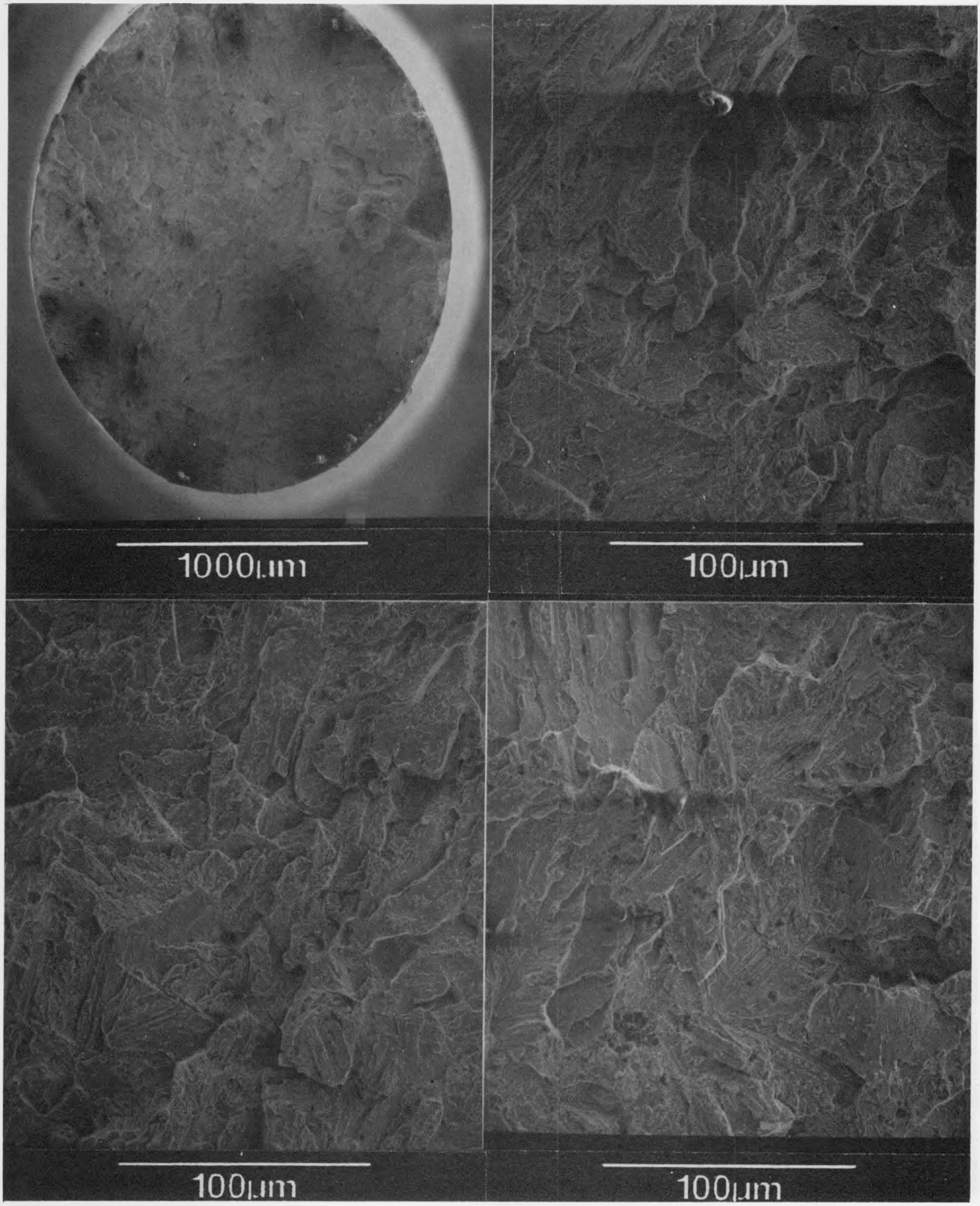

Fig. 23. SEM photographs of a smooth tensile test fracture surface of a sample tested at -54 C, at a strain rate of 0.001 s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

second. Each figure shows one view of the entire fracture surface and three representative views of local areas. The 80°C test shows a typical ductile-dimple fine structure and relatively smooth overall fracture surface. The 24°C tests show a mixture of cleavage surfaces and ductile-dimple areas and a much rougher overall fracture surface. The -54°C test shows a predominantly cleavage surface.

Figures 24, 25, and 26 show the fracture surfaces of notched tensile test samples for tests at a nominal loading rate of 385 MPa per second, and test temperatures of 50°C, 28°C, and -35°C, respectively. All fracture surfaces were rough, with a structure of mixed cleavage and ductile-dimple areas. Figures 27 through 31 show the fracture surfaces of notched tensile test samples, for tests at a nominal loading rate of 12 000 MPa per second and 70°C, 28°C, -35°C, and -50°C. The structure observed in samples tested at the higher loading rate is similar to that found in samples tested at the lower loading rate.

Discussion

The material tested in this report should represent typical cast uranium-3/4 titanium alloy as produced by the Y-12 plant and properly quenched and aged. Wide variations in properties can be expected, however, if the quenching conditions are not severe enough. Hydrogen content is important also because of its embrittling effect. The reported 0.44 wppm of hydrogen for the material tested in this report is considered to be higher than desired. The effect of internal hydrogen is primarily to introduce scatter in mechanical measurements in the form of occasional abnormally low strength and ductility values.

Smooth tensile tests show linear behavior over the -54°C to 80°C temperature range, with yield strength and ultimate tensile strength decreasing with increasing temperature. The mechanical threshold stress model was used to correlate tensile and compressive yield strengths with temperature and strain rate. The model as applied to uranium and the uranium-titanium alloy is

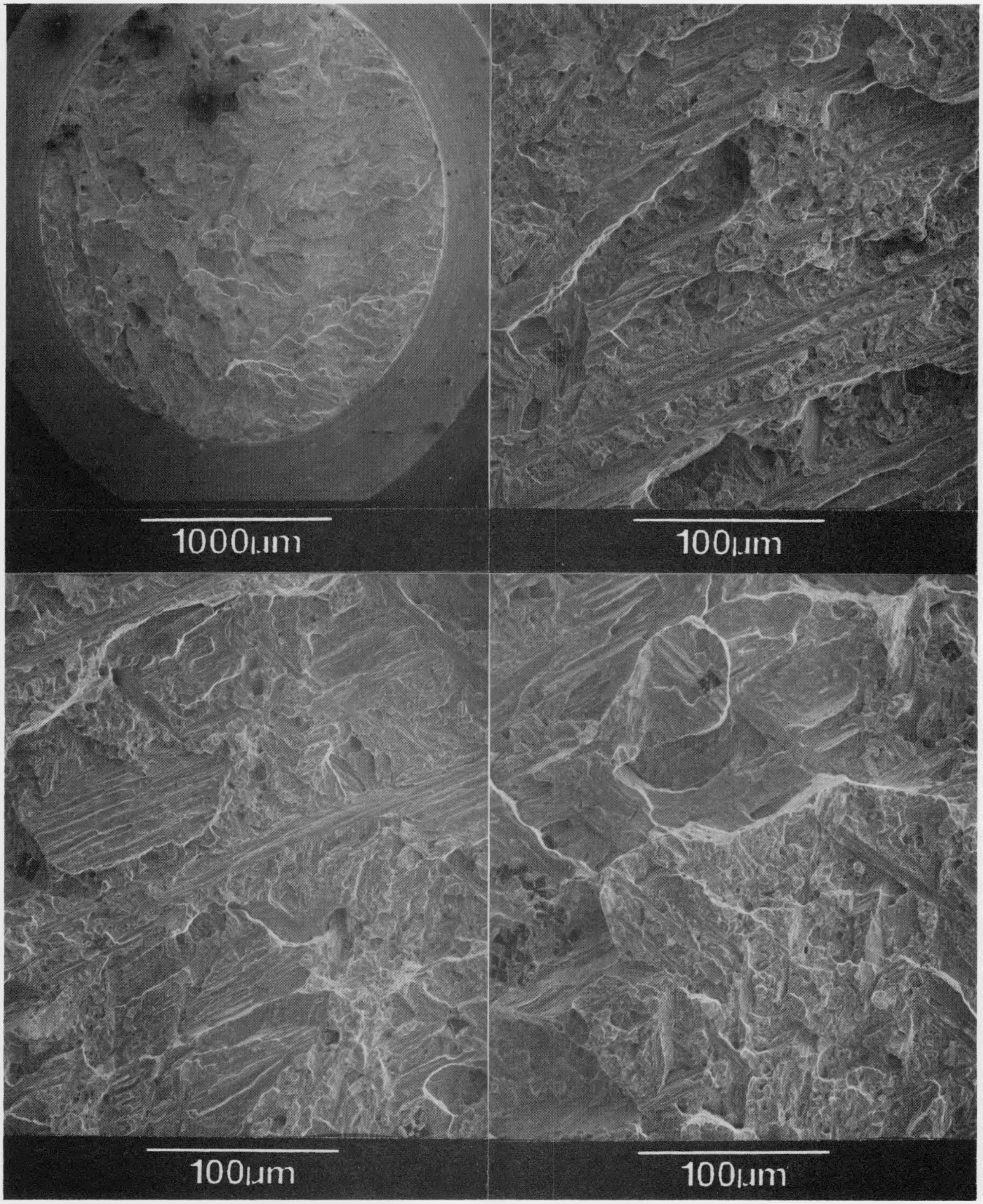

Fig. 24. SEM photographs of a notched tensile test fracture surface of a sample tested at 50 C at a loading rate of 385 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

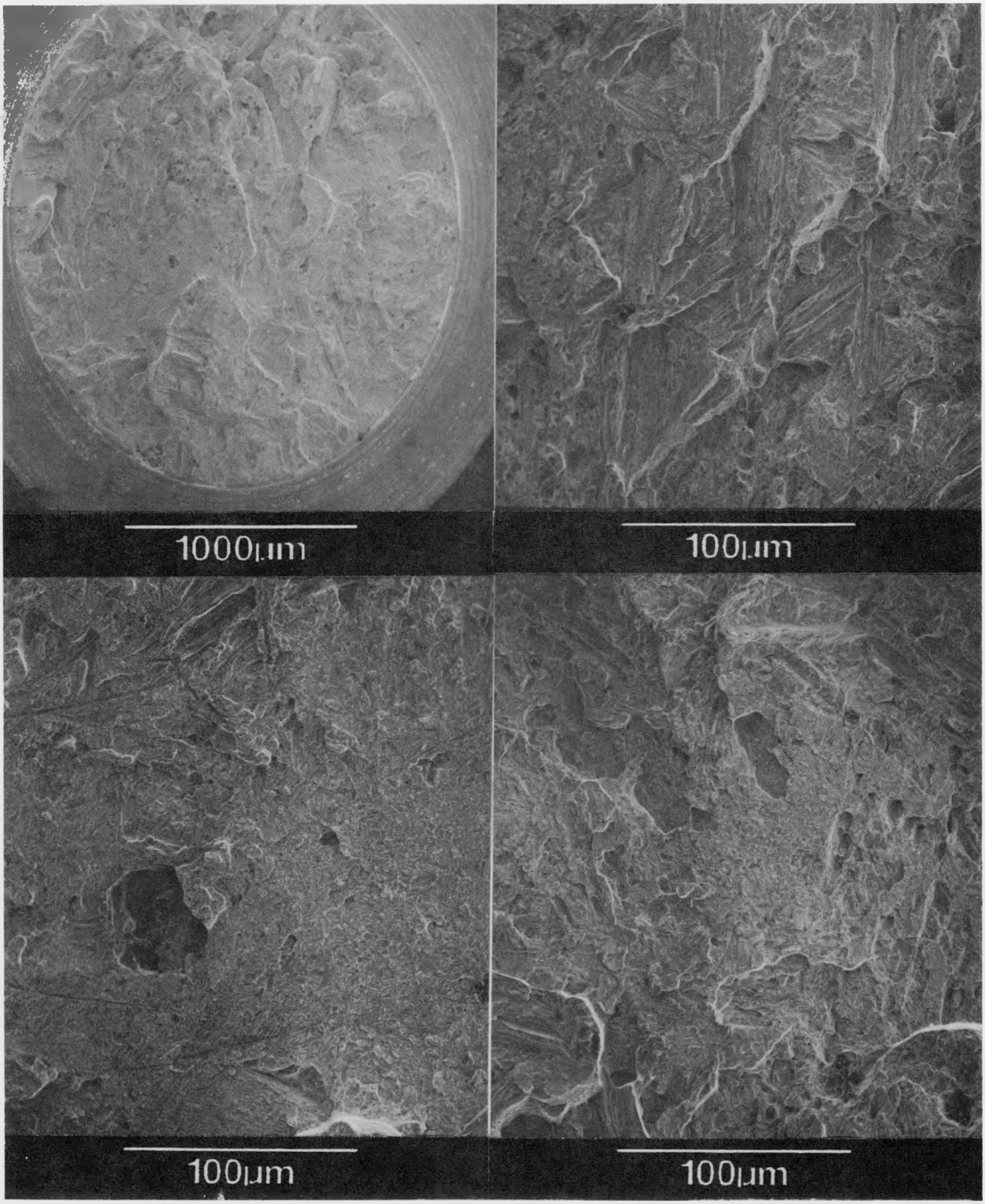

Fig. 25. SEM photographs of a notched tensile test fracture surface of a sample tested at 28 C at a loading rate of 385 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

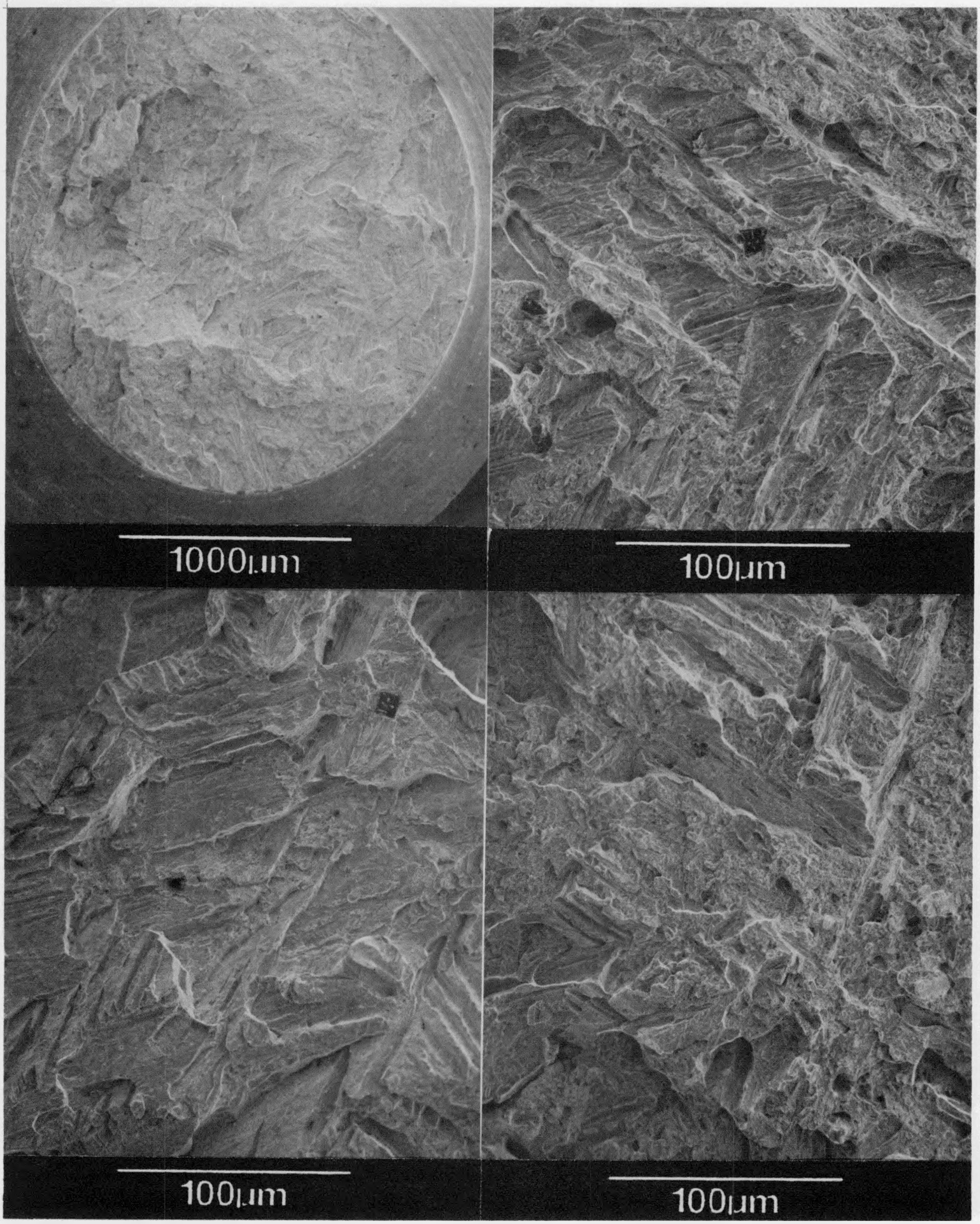

Fig. 26. SEM photographs of a notched tensile test fracture surface of a sample tested at -35 C at a loading rate of 385 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

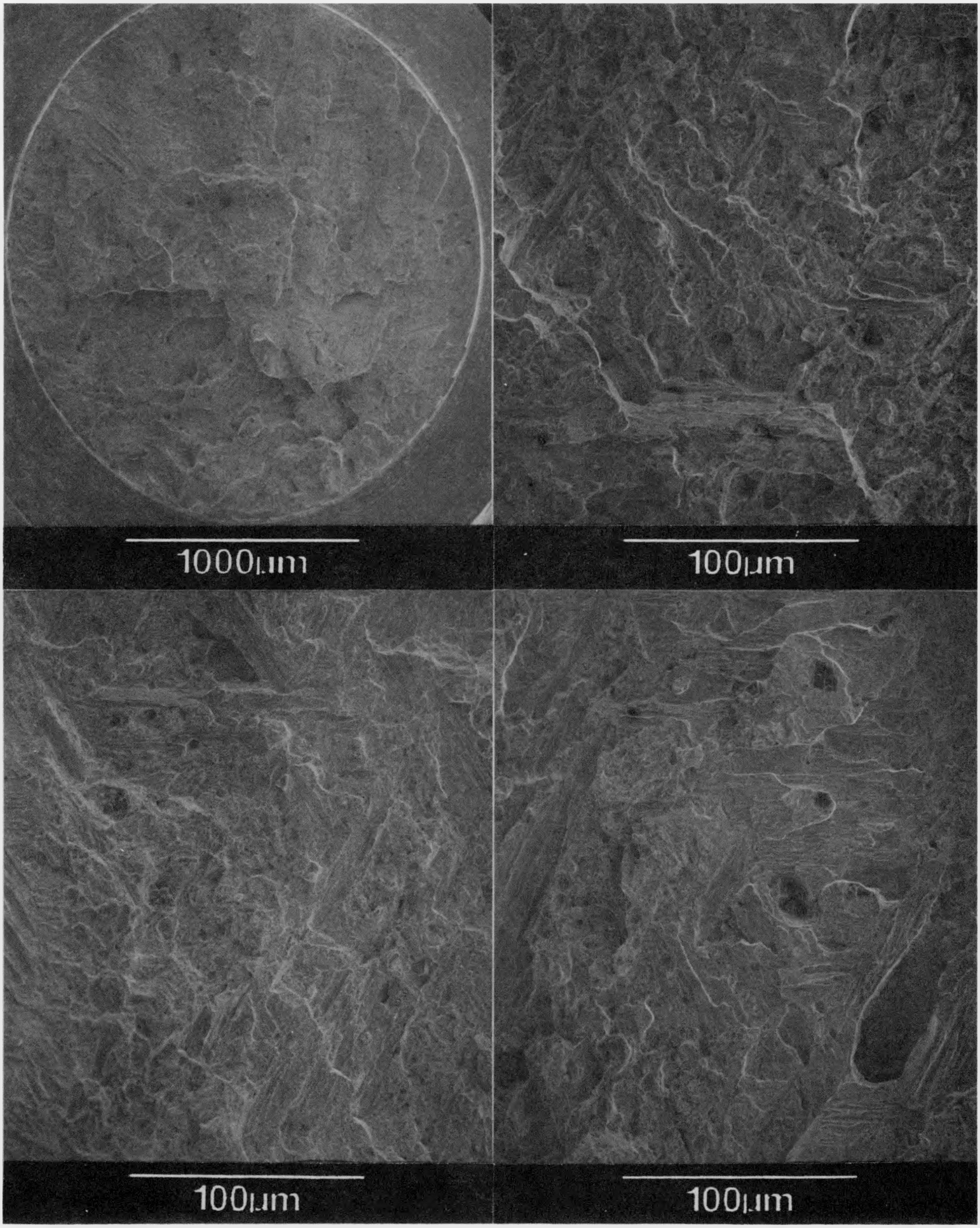

Fig. 27. SEM photographs of a notched tensile test fracture surface of a sample tested at 70 C at a loading rate of 12000 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

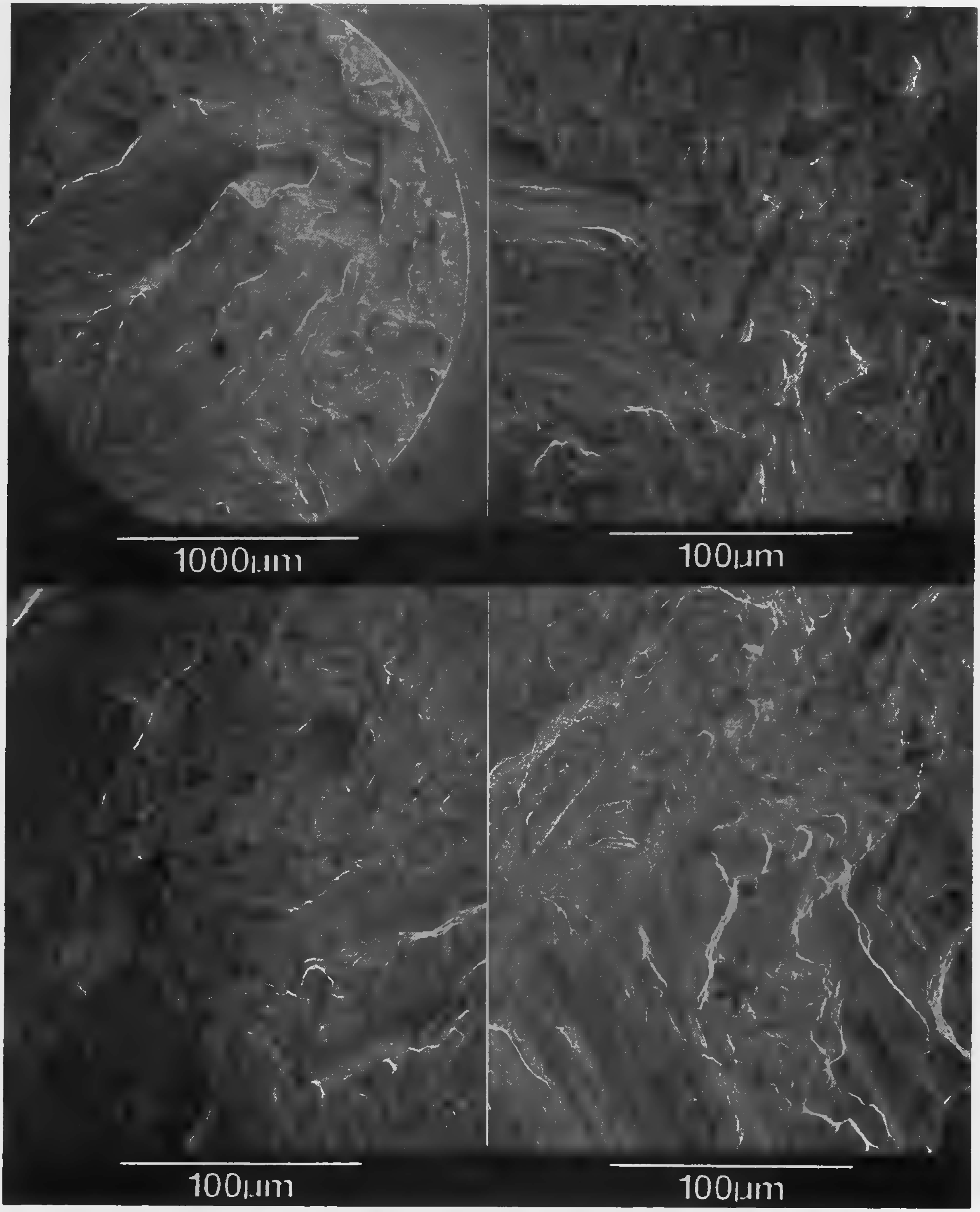

Fig. 28. SEM photographs of a notched tensile test fracture surface of a sample tested at 28 C at a loading rate of 12000 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

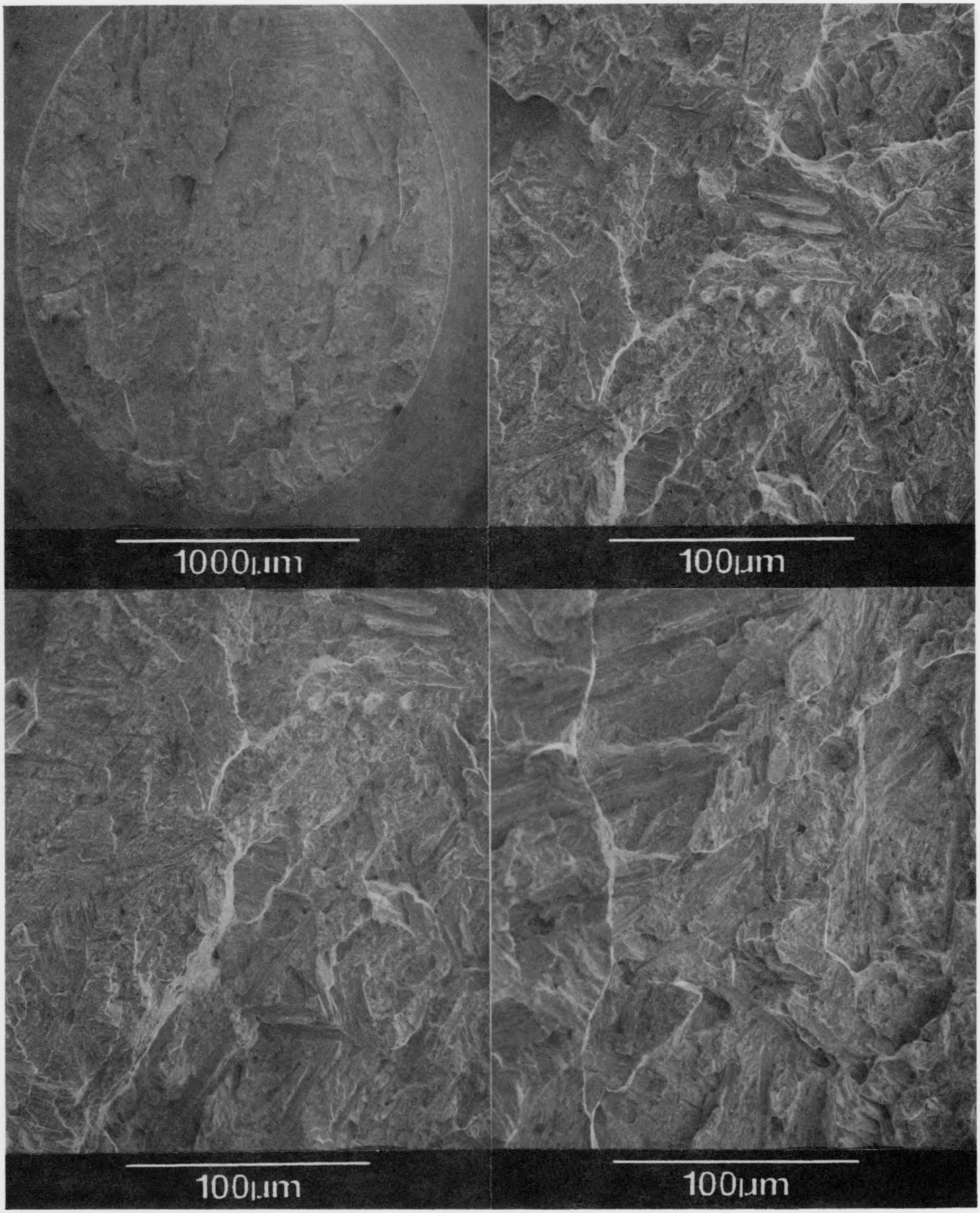

Fig. 29. SEM photographs of a notched tensile test fracture surface of a sample tested at -35 C at a loading rate of 12000 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

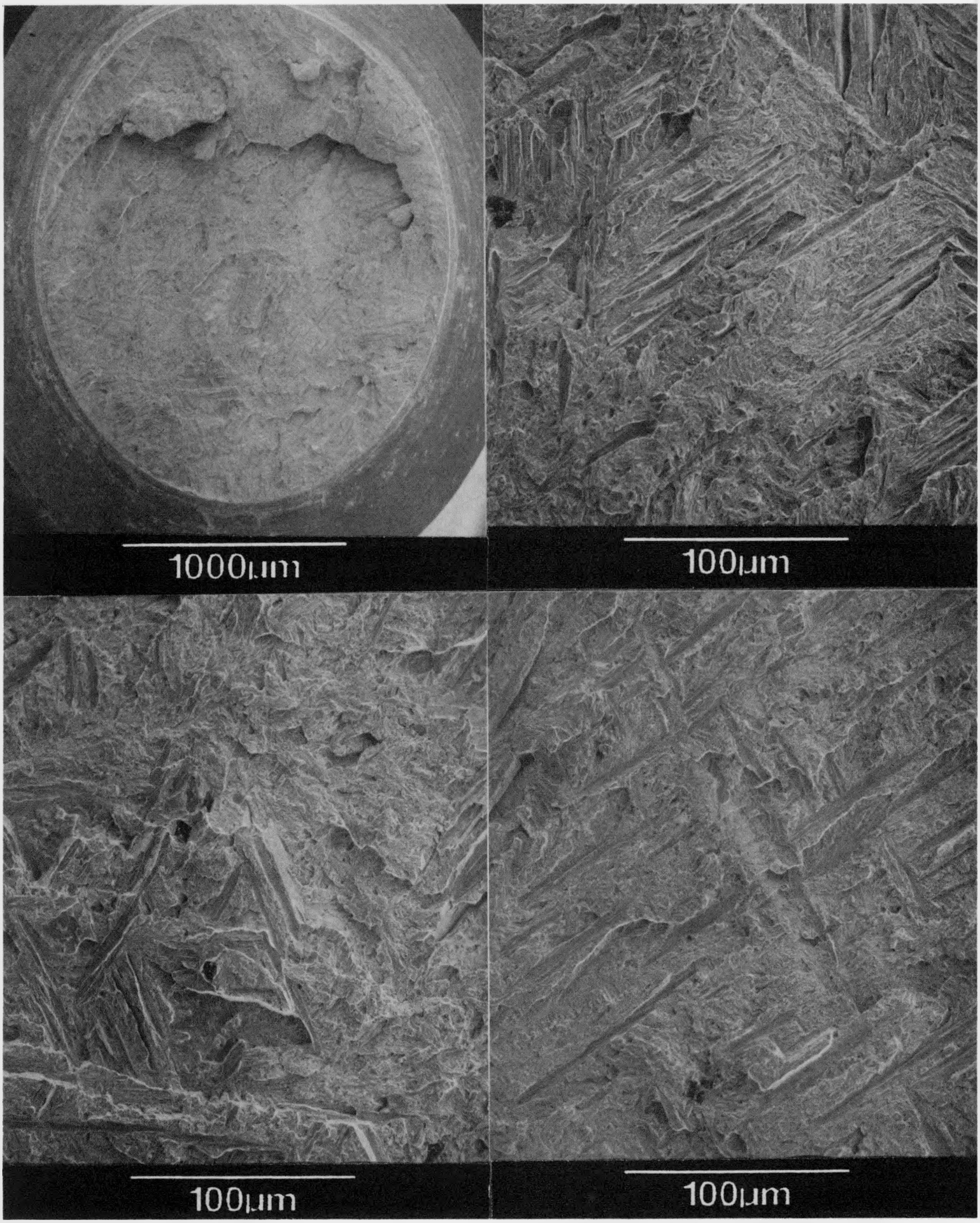

Fig. 30. SEM photographs of a notched tensile test fracture surface of a sample tested at -50 C at a loading rate of 12000 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

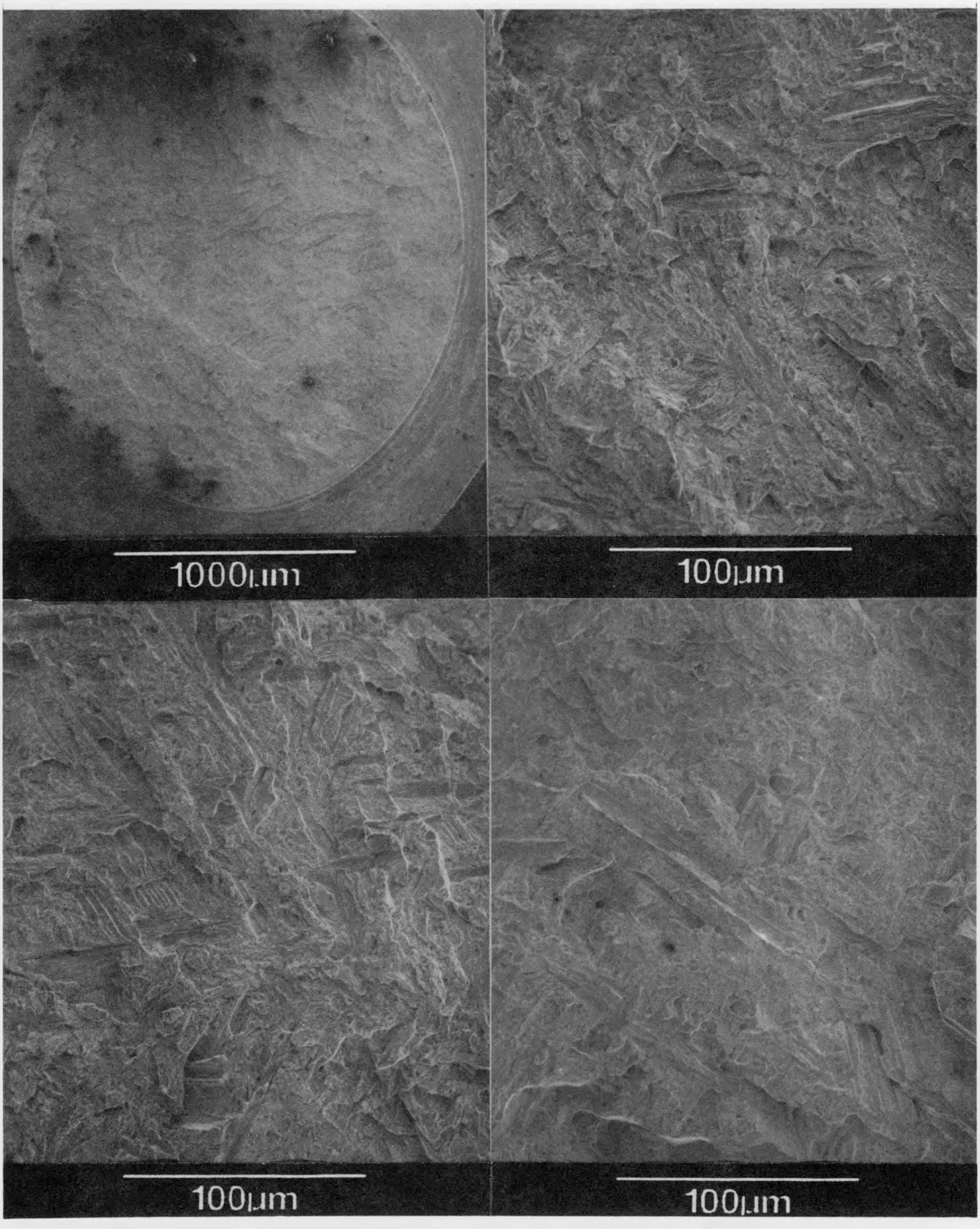

Fig. 31. SEM photographs of another notched tensile test fracture surface of a sample tested at -50 C at a loading rate of 12000 MPa*s-1. Material is U-3/4Ti alloy aged 4 hours at 385 C.

discussed in Appendix A. The considerable scatter in the tensile data makes a precise evaluation of the model parameters difficult for the tensile yield stress, but the results are consistent with the behavior of isotropic unalloyed uranium and with the compression results. There is an obvious difference in compression and tension yield stress, with the compression yield strengths generally about 200 MPa higher than the tensile yield strengths.

Part of the test variability may be due to sampling conditions. The first batch of samples tends to show lower strengths, as shown by the stress-strain curves. Figure 11a shows the curves for the first batch of samples at -54°C, 24°C, and 80°C, at a strain rate of 0.001 per second. The stress-strain curves for the second batch of samples, Fig. 11b, show generally higher strengths. The total elongations measured at -54°C and at 80°C appear to differ in the two batches. Slight differences in quenching rate at different locations in the casting may account for these differences.

Additional aging at 385°C for a total of 8 hours seemed to make little difference in smooth tensile test strengths, but did significantly reduce the ductility, as shown in Figs. 12 and 13a. However, the results of an aging study, Fig. 13b, where the aging temperature was 400°C, show a significant increase in compressive flow stresses with increasing aging times.

Notched tensile tests are useful indicators of fracture toughness, yet these tests are easier to instrument and perform as a function of temperature and atmosphere than are standardized fracture mechanics tests. However, notched tensile tests are not quantitative in themselves and only in certain materials have correlations been established with conventional Charpy impact tests. The notched tensile test is described as an ASTM Standard, E602-81(4), and discussed in relation to aluminum alloys (5). A review article by J.D. Luban, written in 1957, discusses the applicability of the test (6). The strength measured by the test is calculated from the maximum load before fracture divided by the initial minimum notch area. These strengths are compared to the yield and ultimate tensile strengths from smooth tensile tests. A ductile material should exhibit higher notched tensile strengths than corresponding smooth ultimate tensile strengths. This is because the load-supporting area at the bottom of the notch is subjected to a greater triaxiality than the necked region in a smooth tensile test. A brittle material tends to fracture at stresses below the yield stress of a corresponding tensile test. A material that exhibits a ductile-to-brittle transition with decreasing temperature will show notched tensile strengths between the ductile and brittle extremes when tested in the transition temperature range.

The notched tensile test results listed in Table 3 and plotted in Figure 15 show such a transition behavior, with notched tensile strengths exceeding the corresponding ultimate tensile strength at temperatures above -20°C, for the 385 MPa per second test rate, and at temperatures above 20°C for the 12 000 MPa per second test rate. The notched tensile strengths for both rates are above the corresponding yield strengths for all temperatures except the lowest test temperatures, indicating some degree of ductility over most of the range of testing. Another indication of ductility under notched tensile conditions is the maximum notch width change during the test. As shown in Fig. 16, the change is strongly loading rate dependent. One method of reporting notched tensile data is to calculate the notch yield ratio and plot these values versus test temperature. The notch yield ratio is the ratio of notch tensile strength to the corresponding yield strength. Figure 17 shows this plot. There is less scatter in the lower loading rate tests but the trend is the same, with only the -54°C tests having a ratio less than unity. All these tests but one were performed under a protective atmosphere to exclude the possibility of embrittlement from water vapor. One test was conducted in 100% relative humidity air, as listed in Table 3, with no evidence of decreased ductility.

The notched tensile test results can be compared to some limited published data. Jones and Sandstrom (7) tested penetrator cores by the Charpy impact method. Their material was significantly harder than the current material, indicating a higher aging temperature. The hardness of their material was 460 ± 19 DPH, compared to a hardness of 401 ± 16 DPH in the material investigated in the current study. The effect of aging on hardness is shown in Fig. 32, taken from Reference 1. The right-hand DPH hardness scale was derived from data given by Humphreys and Romig (8). The Charpy impact data measured by Jones and Sandstrom showed a smooth non-linear increase in impact energy with increasing temperature, which could be fit by an equation of the form of

$$\text{Impact energy (joules)} = 4.41\, e^{0.0048T},$$

where T = temperature, °C. Because of the higher hardness in this material, one would expect a a lower tensile ductility, and therefore a lower impact energy, than in the material investigated in the current study. They found no detectable effect of microstructural differences between bars (from the initial uneven quenching rates).

From our notched tensile test data, we would expect to see a sharp ductile-to-brittle transition with temperature decrease in Charpy impact tests of 385°C aged material.

Room temperature compression tests showed a strain rate effect, with tests at 0.34 per second and 0.84 per second strain rates having the same low strain (up to about 0.08 true strain) behavior as tests at lower rates, but then showing significantly lower flow stresses at higher strains. This is probably a strain heating effect. These results, shown in Fig. 18, can be compared to the corresponding tensile tests, shown in Fig. 9. The average compression test flow stresses appear to be almost 200 MPa higher than the average tensile test flow stresses, at all strains. This effect persists at all test temperatures, but the effect seems to be highest at 24°C (compare the compression stress-strain curves in Fig. 19 with the corresponding tensile test results in Fig. 11b). One curious result is that the 24°C compression test shows higher flow stress values than the -10°C compression test. The 24°C compression test appears to be anomalously high.

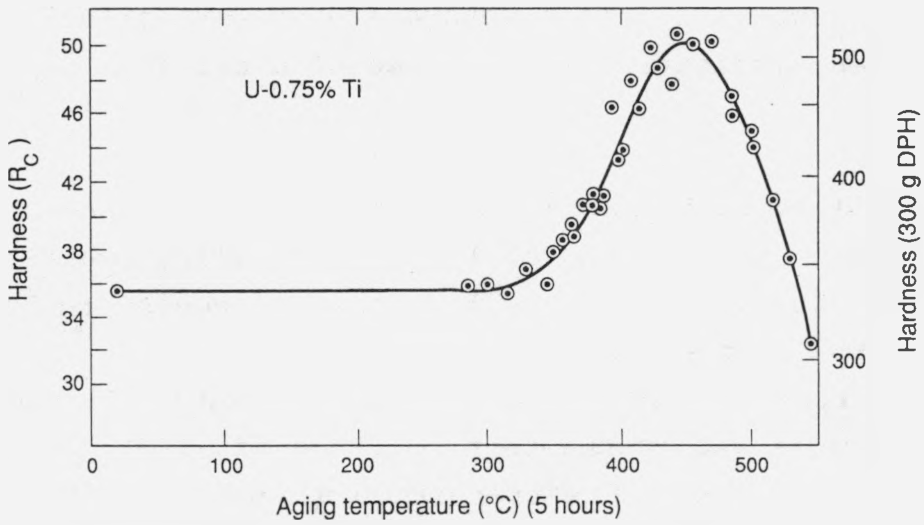

Fig. 32. Hardness versus aging temperature plot from Eckelmeyer(1). Right hand hardness scale added by using the correlation between Rockwell C hardness and DPH hardness of Humphreys and Romig(8).

The SEM photographs of the fracture surfaces reveal a mixture of ductile fractures and cleavage fractures. The ductile fractures are described as having a characteristic ductile-dimple appearance. This results from the classical ductile failure mode where at strains close to the maximum local strain before failure, microvoids are created and grow until the cross section consists of coalescing voids with thin webs between voids. At fracture these webs rupture, leaving the fracture with a dimpled appearance. The smooth tensile test fracture surface of the test at 80°C and slow strain rate (Fig. 20) is almost entirely covered with this structure. The 24°C smooth tensile test fracture surface shows ductile-dimple regions, and many long, narrow cleavage areas with the same average length as the martensite needles shown in the picture of the unstrained material in Fig. 1. At -54°C mostly cleavage areas are observed, perhaps propagating from fractured martensite needles, but with larger and more equiaxial dimensions.

Fracture surfaces from the notched tensile tests show a much rougher appearance at all test temperatures than was observed in fracture surfaces on smooth tensile test specimens. Cleavage along martensite needles is seen at all test temperatures, with increasing occurrence at lower test temperatures. However, regions of ductile-dimple fracture are present at all test temperatures, indicating some degree of ductility.

Summary

* The mechanical properties described in this report should represent expected values for the U-3/4Ti alloy produced by the Martin-Marietta Y-12 plant, with proper quenching followed by aging at 385°C for 4 hours.

* The alloy is considerably stronger than unalloyed uranium at temperatures within the testing range of -196°C to 80°C.

* A ductile-to-brittle transition at about -40°C was observed using notched tensile tests, although microstructural evidence indicated some ductile behavior at all test temperatures.

* Yield strength was correlated with temperature and strain rate by fitting the mechanical threshold stress model (MTS) to both compression and tensile yield data, using the same parameters as for unalloyed uranium, except for the threshold stress strength parameter which was much larger for the U-3/4Ti alloy.

Acknowledgements

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Appendix

The mechanical threshold stress (MTS) model, based on earlier work by Kocks (11,12) and Mecking (13), has been used recently to describe the temperature and strain rate dependence of flow stress for several metals (14,15). Recent measurements on isotropic unalloyed uranium were successfully correlated by this model (9). The model describes the yield stress dependence on strain rate and test temperature and accounts for the change in flow stress with increasing strain (strain hardening).

For U-3/4 Ti the model was applied only to yield strength measurements. The model describes the yield stress dependence on the current temperature, T, the current strain rate, $\dot{\varepsilon}$, and the current state, represented by a mechanical threshold stress which characterizes dislocation interactions with obstacles. The mechanical threshold stress represents the cumulative effect of threshold stresses for various types of interactions. The simplest interpretation is that there is a relatively small threshold stress characterizing athermal dislocation interactions, $\hat{\sigma}_a$, and only one important mechanical threshold stress characterizing thermally activated interactions. This relationship can be expressed as:

$$\sigma/\mu = \hat{\sigma}_a/\mu + s(\dot{\varepsilon},T) * \hat{\sigma}/\mu \qquad \text{(A1)}$$

where one useful form of the function, s, that has physical significance when applied to dislocation/obstacle interactions is written as:

$$s = [1-(k/b^3 g_o * \ln(\dot{\varepsilon}_o/\dot{\varepsilon}) * T/\mu)^{(1/q)}]^{(1/p)} \qquad \text{(A1a)}$$

In these equations, p and q are constants describing obstacle characteristics, μ is the temperature dependent elastic shear modulus, $\hat{\sigma}_a$ is the athermal mechanical threshold stress, $\hat{\sigma}$ is the mechanical threshold stress for thermally activated dislocation interactions, $\dot{\varepsilon}_o$ is the reference strain rate, k is the Boltzmann constant, b is the Burgers vector, g_o is the total normalized activation energy, and σ is the yield stress. Combining Eqs. (A1) and (A1a) and re-arranging terms gives

$$((\sigma-\hat{\sigma}_a)/\mu)^p = (\hat{\sigma}/\mu)^p-(\hat{\sigma}/\mu)^p(k/b^3/g_o)^{(1/q)}(\ln(\dot{\varepsilon}_o/\dot{\varepsilon})T/\mu)^{(1/q)} \quad (A2)$$

The parameters in Eq. (A2) were determined for unalloyed uranium by trial-and-error iterations until a "best fit" to the over 180 test results at different conditions was achieved. Plots of $((\sigma-\hat{\sigma}_a)/\mu)^p$ versus $(\ln(\dot{\varepsilon}_o/\dot{\varepsilon})T/\mu)$ were linear when p=2/3, q=1, and $\hat{\sigma}_a$=60. Since g_o was expected to be a constant, inspection of Eq. (A2) showed that the term $(\hat{\sigma}/\mu)$ must remain constant for all values of T and $\dot{\varepsilon}$, and the intercept at T=0 equates to $(\hat{\sigma}_o/\mu_o)^p$. Thus the slope can be evaluated to obtain a value for g_o.

With the limited temperature and strain rate range of data available for the aged U-3/4Ti alloy from this study, an independent fitting of Eq. (A2) was not feasible. Rather, the values of p, q, $\dot{\varepsilon}_o$, and g_o from the isotropic uranium study were used to evaluate the magnitude of the mechanical threshold stress by trial-and-error fitting of Eq. (A2) to the data. The results of this procedure are shown in Fig. A1 for two compression test yield criteria and one tensile yield criterion. The curves labeled "Compression Yield" and "Tensile Yield" were constructed from stress-strain curve yield strengths using a 0.2 percent strain offset method. The curve labeled "Back Extrapolated Compression Yield" was obtained from the same plots by observing the intersection of a continuation of the linear elastic deformation initial part of the stress-strain plot, with a back-extrapolation of the plastic strain region. This method allows for some small plastic deformation but gives an experimentally more reproducible result. Both compression curves show a reasonable fit to the data, while the tensile data show much more scatter. It is obvious that the tensile yield stress values are significantly lower than the results of either of the compression yield methods. Table A1 lists the parameters used to construct the curves from Eq. (A2).

A useful form of Eq. (A2) for calculating yield strength as a function of temperature and strain rate for the conditions in Table A1 is written as

$$YS(MPa) = 60 + \mu[(\hat{\sigma}_o/95290)^{2/3} - (\hat{\sigma}_o/95290)^{2/3}(0.5938/g_o)*\ln(\dot{\varepsilon}_o/\dot{\varepsilon})T/\mu]^{3/2}. \quad (A3)$$

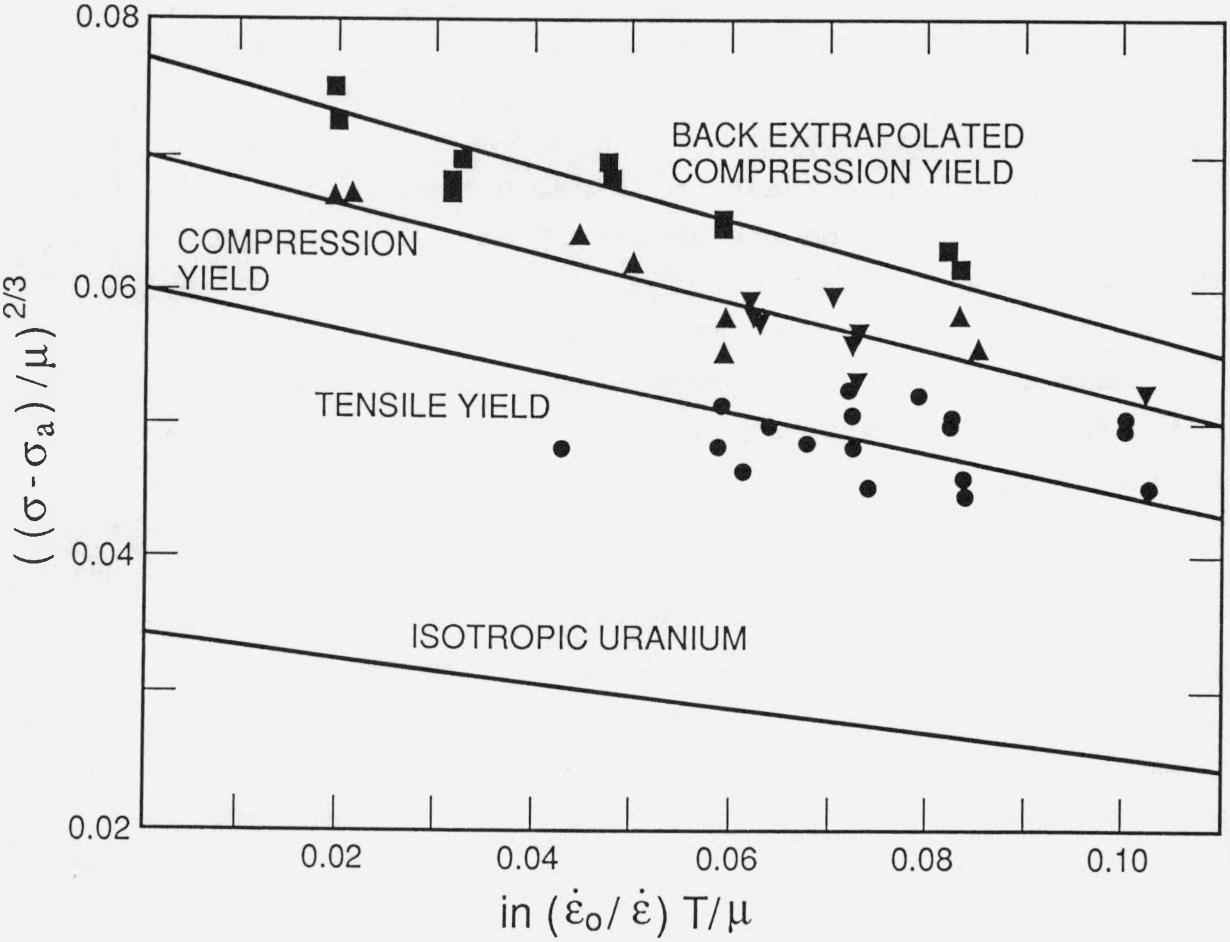

Fig. A1 MTS modeling of yield strength of U-3/4Ti alloy aged 4 hours at 385°C, compared to isotropic uranium. Compression yield ▼ symbols are from compression samples prepared from tensile test specimen ends, and ▲ symbols are from larger compression specimens.

TABLE A1

Parameters for the MTS Model for Aged U-3/4Ti and Uranium

Parameter	Units	Unalloyed U	Tension	Compression	Back Extrapolated
p		2/3	2/3	2/3	2/3
q		1	1	1	1
$\hat{\sigma}_a$	MPa	60	60	60	60
g_o		0.23	0.23	0.23	0.23
$\dot{\varepsilon}_o$	s^{-1}	10^7	10^7	10^7	10^7
μ_o(1)	MPa	95290	95290	95290	95290
$\hat{\sigma}_o$	MPa	600	1401	1761	2036
k	MNm/K	$1.381*10^{-29}$			
b(2)	m	$2.854*10^{-10}$			
s	MPa				
T	K				

1) $\mu = 1000(95.29 - .05009T + 2.856*10^{-5}T^2 - 4.099*10^{-8}T^3)$, from Ref.9.

2) Average Burgers vector for unalloyed uranium, assumed to be approximately correct for the U-3/4 Ti Alloy.

A useful form of Eq. A2 for calculating yield strength as a function of temperature and strain rate is:

$$Y.S(MPa)=60+ \mu[(\hat{\sigma}_o/95290)^{2/3}-(\hat{\sigma}_o/95290)^{2/3}*.5938/g_o*\ln(\dot{\varepsilon}_o/\dot{\varepsilon})T/\mu]^{1.5}$$