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Some Effects of Low Temperatures and Notch Depth on the Mechanical Behavior of an Annealed Commercially Pure Titanium[1]

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Unnotched and notched specimens (60° notch angle, 0.05-inch root radius and various notch depths) of an annealed commercially pure titanium were slowly strained to fracture in tension at +150° or +100° to −196° C, to reveal the combined effects of temperature and notch geometry on the tensile behavior of the metal. Impact tests were made on Charpy V-notch specimens at +300° to −196° C for a determination of the impact notch-toughness of the titanium. True stress-true strain relations were determined for the titanium in tension and a study was made of the effects of test temperature, stress system, and interstitial content on the mechanism of deformation and work-hardening characteristics of the metal.

1. Introduction

Several investigators [1 to 5][2] have published results of their studies to determine the mechanisms involved in the tensile deformation of unnotched specimens of titanium and some of its alloys. The data obtained on single crystals [4,5] and on coarse-grained polycrystalline specimens [1,2,3] indicate that the tensile properties and the mechanisms involved in the tensile deformation of alpha titanium are quite temperature sensitive and complex. A large proportion of the deformation in tests at −196° C was by twinning [1,2]; the amount of twinning, in general, decreased with increase in temperature. Single and duplex slip on the prismatic planes also occurred in the deformation at −196° C [1,4]. With increase in temperature to +25° C, slip was observed on prismatic planes and also on pyramidal planes [1,4] and the basal plane [2]. The amount of slip on pyramidal planes increased considerably as the temperature was raised to +500° and +800° or +815° C [1,3].

Very few data are available on the combined effect of notches and low temperatures on the tensile behavior of titanium and its alloys; most of the published data were obtained on titanium alloys either in tests at different temperatures on specimens with a constant notch geometry [6,7,8], or in tests at room temperature on specimens of selected notch depths [9]. Results obtained at the Bureau in tension tests at different temperatures on a heat of annealed commercially pure titanium [10] contained some data on notched specimens of selected notch depths. However, the quantity of titanium available for these tests was relatively small, and only an exploratory investigation of the effect of low temperatures on the properties of notched specimens was possible.

An additional heat of commercially pure titanium was procured for use in the present study of the combined effects of low temperatures and notch geometry on the tensile behavior, as a part of a comprehensive program at the Bureau to evaluate the fundamental factors affecting the deformation of metals. The present paper summarizes the data obtained at low temperatures in Charpy V-notched impact and in tension on both unnotched and notched specimens of selected notch depths of this heat of titanium.

2. Material and Test Procedures

2.1. Material

All test specimens were prepared from bars processed from a single heat of commercially pure titanium (ASTM Designation B265–52T, grade 2). The bars were supplied in the form of 1-in. rounds in the hot-rolled and annealed condition; the bars were fine grained (fig. 1). The impurities (numerical values are in percent by weight) determined[3] in the titanium were as follows: Oxygen, 0.21; nitrogen, 0.04; hydrogen, 0.012; carbon, 0.04; silicon, 0.02; iron, *W;* chromium, *W;* tin, *W;* aluminum, *VW;* magnesium, *VW;* manganese, *VW;* nickel, *VW;* copper, *T;* tungsten, not determined.

2.2. Specimens

The forms and dimensions of the tensile specimens are shown in figure 2. The reduced section ($D=0.40$ in.) of the unnotched specimens was slightly tapered. The notched specimens were machined with a constant root radius of 0.05 in. and a constant minimum diameter, d, of 0.35 in., thereby minimizing the size effect. The notch depth[4] was varied by changing the diameter, D, of the cylindrical portion of the specimen adjacent to the notch.

ASTM standard (E23–47T) Charpy V-notch specimens were prepared from one bar of the titanium.

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[1] This investigation was partially supported by the Materials Laboratory, Directorate of Research, Wright Air Development Center, USAF.

[2] Figures in brackets indicate the literature references at the end of this paper.

[3] Chemical analysis determinations for nitrogen, carbon, and silicon were made by the Analytical Chemistry Section of NBS. Determinations for oxygen and hydrogen were made by D. I. Walter at the Naval Research Laboratory by a modified vacuum fusion method [11]. The spectrographic-analysis determinations designated by letters were made by the Spectrochemistry Section of NBS. In general, W denotes weak (0.01 to 0.1%), VW denotes very weak (0.001 to 0.01%), and T denotes trace (0.0001 to 0.001%). The spectrographic method used was not sensitive for determination of tungsten.

[4] Notch depth is expressed as the percent of cross-sectional area removed in machining the notch in the specimen and it is equal to $100\,(D^2-d^2)/D^2$.

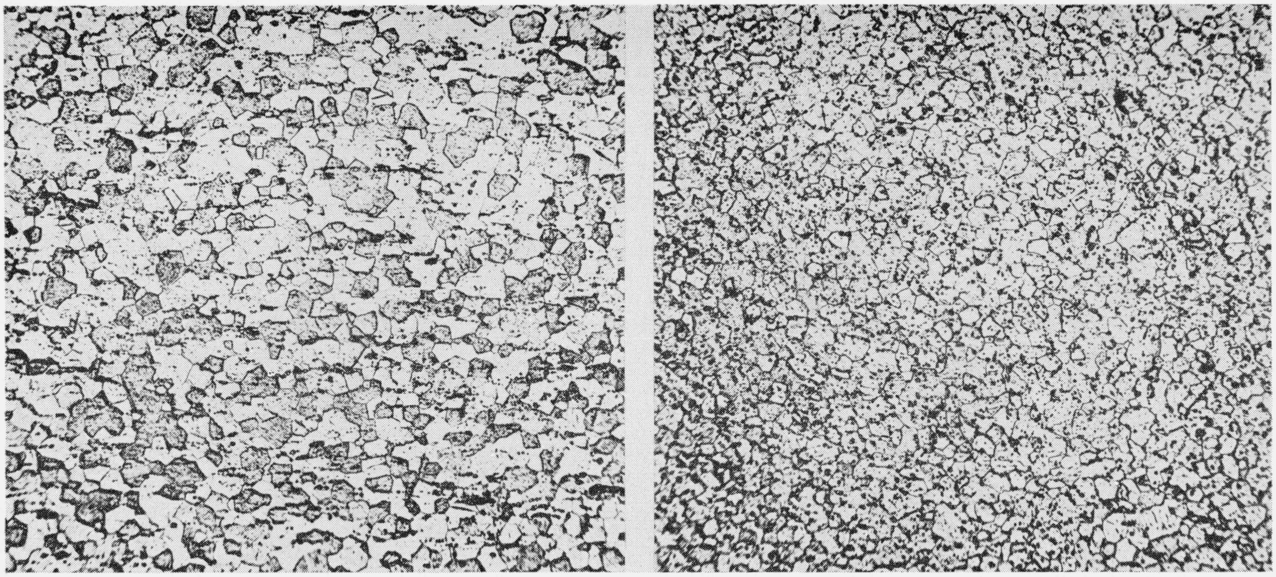

FIGURE 1. *Microstructure of the annealed commercially pure titanium.*

X 100. Left, longitudinal section; right, transverse section. Etchant: 1 part HF, 10 parts HCl, 10 parts HNO_3 and 80 parts water.

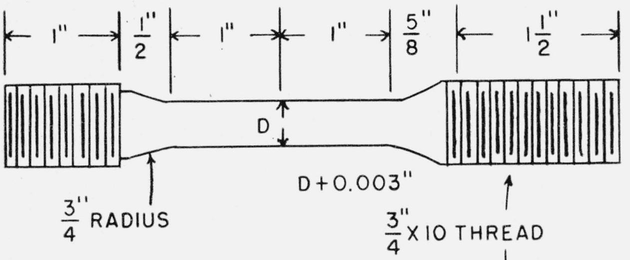

FIGURE 2. *Dimensions and forms of notched and unnotched tensile specimens.*

2.3. Test Procedures

The Charpy V-notch tests were made at temperatures ranging from +300° to −196° C in a machine of 224.1 ft-lb capacity and a striking velocity of 16.85 ft/sec. The specimens, except those tested at room temperature (about +25° C), were immersed in a bath at the selected temperature for a minimum period of 30 min, and then quickly transferred to the impact machine and broken. The total time elapsing between the removal from the bath and the breaking of the specimens ranged from 3 to 4 sec and there was no significant change in the temperature of the specimens during this period.

A detailed description of the tensile test equipment and the method of maintaining the selected temperature is given in previous publications [12, 13, 14]. The tensile tests were made at temperatures ranging from +150° or +100° C to −196° C with notched and unnotched specimens in a pendulum hydraulic testing machine. The specimens were strained slowly with the deformation rate maintained at about 0.5 to 1.0 percent reduction in area per minute during the deformation beyond initial yielding. The specimens, except those tested at room temperature, were strained to fracture while completely immersed in an appropriate bath maintained at the selected temperature. The specimens were immersed in the bath for a period of 30 min prior to the application of load. Simultaneous load and diameter (minimum diameter of unnotched specimens, diameter at base of the notch of the notched specimens) measurements were made throughout each tension test.

3. Results and Discussion

3.1. Impact Tests

The results obtained in the impact tests are summarized in figure 3. A transition temperature of about +110° C was indicated by the criteria of either (1) the steepest slope of the energy-temperature curve or (2) the mean value of the energy absorbed at the lowest temperature, and at the highest temperature at which complete fracture occurred. These impact data differed appreciably from those obtained previously [10] on another heat of commercially pure titanium with relatively small amounts of interstitials, which had a transition temperature about *40° C higher*, and a considerable degree of notch toughness (10 ft-lb, energy absorbed) at −196° C. This difference in the notched-bar impact behavior of these two heats of annealed commercially pure titanium may be attributed to the effects of the interstitial elements (carbon, nitrogen, oxygen, and hydrogen) as the other impurities did not vary significantly. The observed lower notch toughness (energy absorbed) at temperatures below the transition temperature range of the present heat of titanium with the higher interstitials, and thus with the higher hardness and strengths, conforms to the normal behavior for metals. However, the observed lower transition temperature for this heat of titanium is surprising, and no satisfactory explanation for this behavior can be given at the present time. As the grain size of the previous heat of titanium with low interstitials was slightly finer than that of the present heat, the difference in the transition temperatures cannot be readily attributed to a grain size effect.

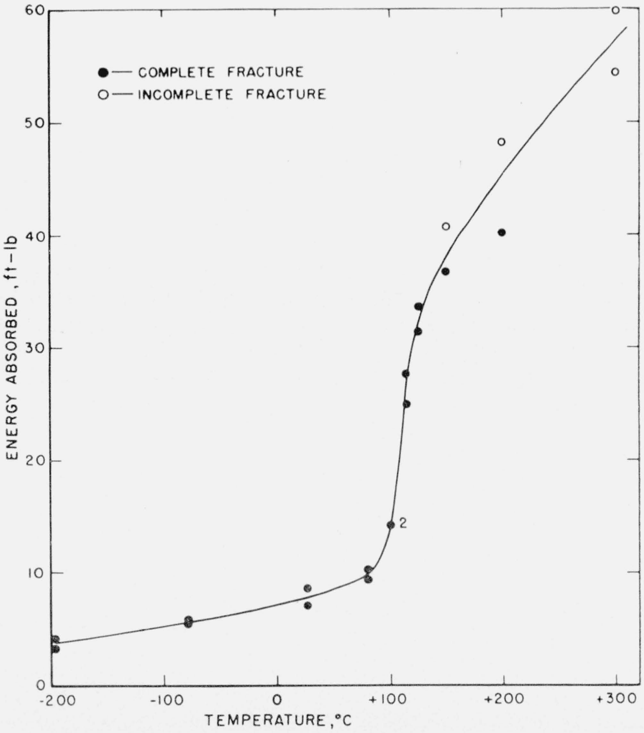

FIGURE 3. *Relation of temperature to the energy absorbed in fracturing the Charpy V-notch specimens.*

3.2. Tensile Tests

a. Flow Curves

The true stress-true strain relations obtained in tension tests on unnotched specimens at different temperatures are presented in figure 4. The true stress [5]-true strain [6] values that were obtained in duplicate tests at +100°, +25°, and −196° C were fairly consistent and showed only slight deviations from the curves representing the average values at each temperature. The marked effect of temperature on the strength of the titanium is shown by the increase in height of the true stress-true strain curves as the temperature is lowered. The initial resistance of the metal to plastic flow at −196° C is more than three times that at +150° C.

Logarithmic graphs of the true stress-true strain data (not shown) were sigmoidal. These data, like those obtained previously on another heat of titanium [10], and on other metals [13, 14], do not conform to the often postulated relationship, $\sigma = k\delta^m$, for tensile deformation, where σ and δ are the true stress and true strain, respectively, and k and m are constants.

The true stress-true strain relations obtained in tension tests at +100°, +25°, −78°, and −196° C on circumferentially notched specimens are presented

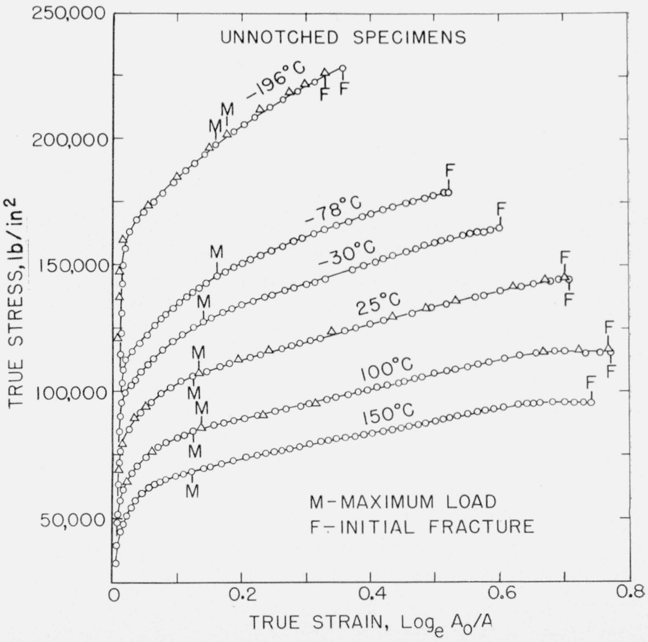

FIGURE 4. *True stress-true strain relations obtained in the tension tests at different temperatures on unnotched specimens.*

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[5] True stress, σ, was determined by dividing the current load by the current minimum cross-sectional area of the specimen

[6] True strain, δ, was determined as the natural logarithm of the ratio of the original minimum cross-sectional area of the specimen A_0, to the current minimum cross-sectional area, A.

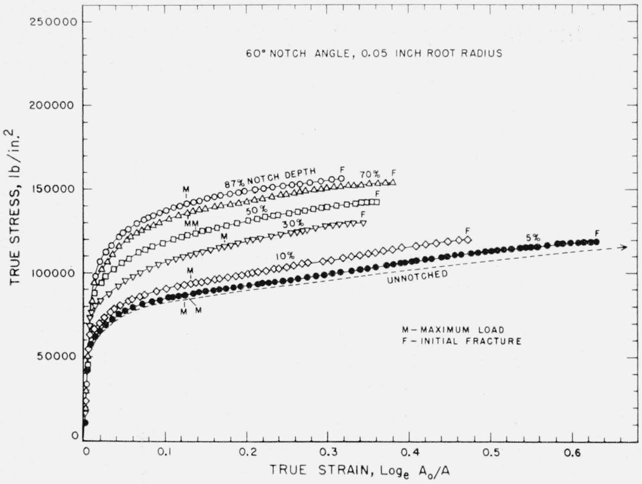

FIGURE 5. *True stress-true strain relations obtained in the tension tests at +100° C on notched specimens.*

in figures 5 to 8, respectively. Portions of the true stress-true strain curves for unnotched specimens are also included in these graphs. The resistance of the metal to flow, in general, increased with (1) decrease in temperature, (2) increase in the triaxiality accompanying increase in notch depth, and (3) increase in true strain. At each temperature, the increase in the resistance to flow with increase in notch depth became relatively small as the notch depth was increased above 70 percent. This is to be expected, because the increase in triaxiality was also relatively small as the depth was increased from 70 to 87 percent.

Both the stress concentration and the triaxiality induced in a notched specimen in a tensile test vary with the geometry of the notch. The variation of these factors with the notch depth for the titanium specimens of circular cross section containing a circumferential notch of 60° angle and 0.05-in. root radius, is shown in figure 9. The values for the stress concentration factor K_t, were derived from published stress concentration design charts [15]. The triaxiality, determined as the ratio S_t/S_l, where S_t and S_l are the transverse and longitudinal stresses, respectively, is based on the method proposed by Sachs and Lubahn [16]; that is, $S_t/S_l = 1-(1/R)$, where R is the ratio of notch strength[7] to the tensile strength. The triaxiality increases at a nearly constant rate with increase in notch depth to about 20 percent, and then increases at a continuously decreasing rate with further increase in notch depth. The stress concentration factor increases very rapidly with increase in notch depth to about 10 percent, less rapidly with increase in depth from 10 to 30 percent and then increases only slightly with further increase in the depth.

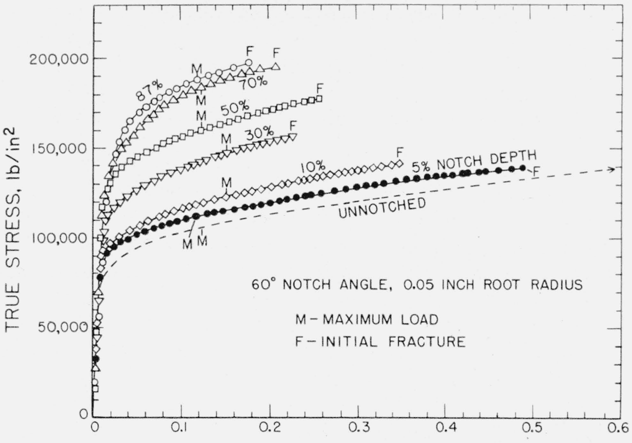

FIGURE 6. *True stress-true strain relations obtained in the tension tests at +25° C on notched specimens.*

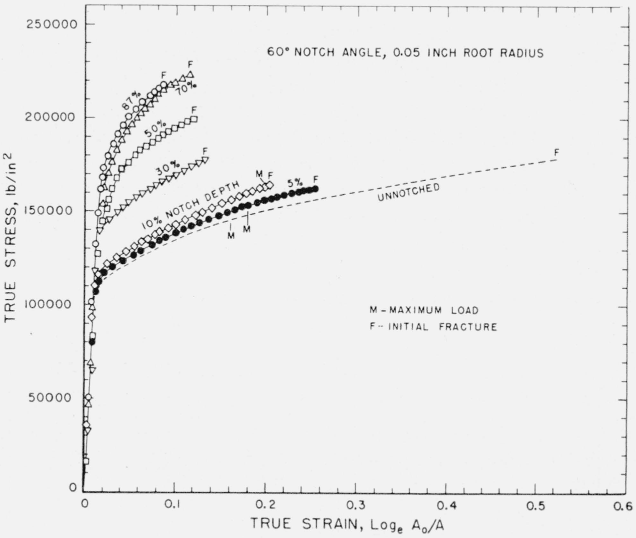

FIGURE 7. *True stress-true strain relations obtained in the tension tests at −78° C on notched specimens.*

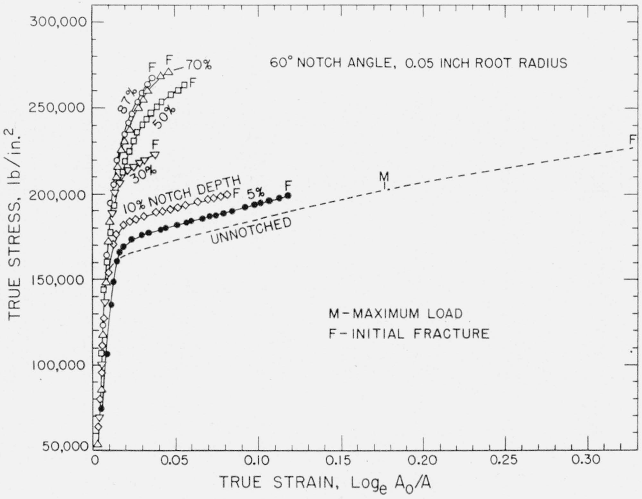

FIGURE 8. *True stress-true strain relations obtained in the tension tests at −196° C on notched specimens.*

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[7] Notch strength was determined by dividing the highest load attained on the notched tensile specimen by the original minimum cross-sectional area at the notch. In determining the values of R, the notch strength values are restricted to those in which the specimen had sufficient ductility to attain a normal maximum load condition, that is, the slope of the load-extension curves becomes zero.

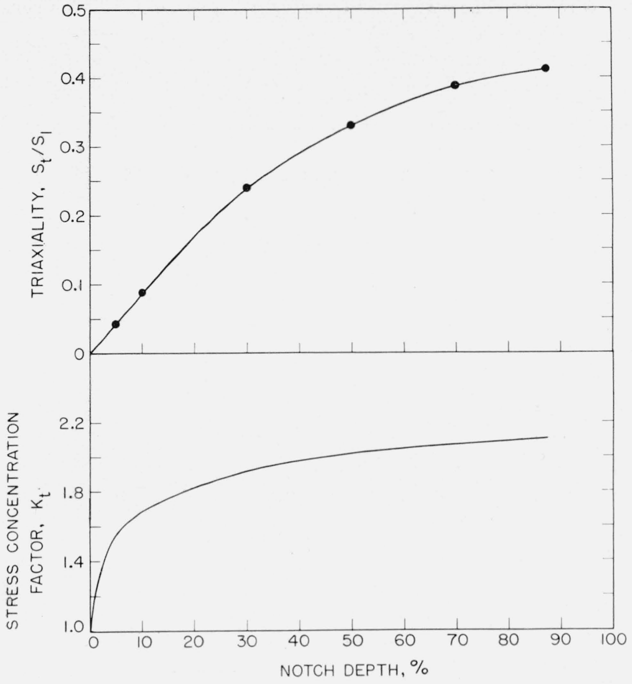

FIGURE 9. *Effect of notch depth on the stress concentration factor and the triaxiality of the tensile specimens used.*

(60° notch angle, 0.05-in. root radius, and 0.350-in. diameter at the base of the notch.)

b. Effects of Temperature and Notch Geometry

(1) *Strength Indices.* The results of the tensile tests on unnotched and notched specimens are summarized in tables 1 and 2, respectively. A determination of yield strength, as normally based on offset values from autographic load-extension curves, was not feasible with the equipment employed. However, an indication of the stresses at which appreciable yielding has taken place is given by the values of true stress at a true strain (elastic plus plastic) of 0.02. These "0.02 stress" values would be higher than the 0.2 percent offset yield strength values for unnotched specimens, particularly at the higher temperatures because the amount of elastic strain prior to yielding, in general, increased with lowering of temperature and with increase in notch depth.

The relations between the 0.02 stress of the titanium and the notch depth and temperature are represented by the surface delineated in figure 10. The 0.02 stress at each test temperature increased, at a slightly decreasing rate, with increase in notch depth; the values for the specimens with the deep notches (70 and 87% notch depths) were approximately one and one-half times those for unnotched specimens at corresponding temperatures. A relatively large increase in the 0.02 stress was observed for both the notched and unnotched specimens with decrease in temperature from +100° to −196° C; the strengths of the specimens at −196° C were greater than those of corresponding specimens at +100° C by factors of 2.5 for unnotched specimens and 2.7 to 2.2 for the notched specimens (table 3). No simple relation between 0.02 stress and temperature is indicated as the curves (fig. 10) representing the variation of the stress with temperature for specimens of the same notch depth have an inflection point near 0° C. The inflection point may be an indication of a significant increase in the number of active slip plane systems and accompanying decrease in the stress for activation of slip with increase in temperature above 0° C.

TABLE 1. *Tensile properties at +150°, +100°, +25°, −30°, −78°, and −196° C of unnotched specimens of initially annealed commercially pure titanium*

Specimen [a] designation	Temperature	Tensile strength	True stress			True strain [b]		Reduction of area	Elongation [c] in 2 in.
			At true strain of 0.02	At maximum load	At initial fracture	At maximum load	At initial fracture		
	° C	*lb/in.²*	*lb/in.²*	*lb/in.²*	*lb/in.²*			*%*	*%*
B10	+150	60, 000	50, 000	69, 000	95, 000	0. 121	0. 741	52	44
B8	+100	75, 000	64, 000	85, 000	115, 000	. 123	. 774	57	40
B6	+100	75, 000	63, 000	86, 000	117, 000	. 137	. 770	57	42
B1	+25	94, 000	84, 000	106, 000	144, 000	. 123	. 708	53	30
B9	+25	94, 000	84, 000	108, 000	145, 000	. 136	. 703	51	30
B5	−30	111, 000	100, 000	128, 000	165, 000	. 140	. 602	45	26
B2	−78	124, 000	113, 000	146, 000	179, 000	. 160	. 522	42	26
B7	−196	169, 000	164, 000	202, 000	227, 000	. 176	. 330	29	20
B4	−196	169, 000	157, 000	198, 000	229, 000	. 159	. 358	31	22

[a] All specimens were prepared from the same bar, B.

[b] Includes elastic and plastic deformation.

[c] Measurements based on punch marks in fillets. Specimens had a reduced section of 2.0 in. length.

The observed relations between the notch strength of the titanium and the notch depth and temperature are represented by the surface delineated in figure 11. The shape of this surface is nearly similar to that shown for the 0.02 stress (fig. 10). As shown in figure 12, the percentage increase in notch strength is approximately equal to the notch depth for depths up to 50 percent. However, nearly all of the values for notch depths of 70 and 87 percent lie considerably below the dotted line representing the above relationship. This deviation may be attributed partially to the relatively low rate of increase in triaxiality with increase in notch depths for depths greater than 50 percent (fig. 9). A considerable portion of the deviation of the values for the deep-notched specimens at −78° and −196° C may be attributed to the very small ductility of these specimens (table 2).

The combined effects of temperature and notch depth on the true stresses at maximum load and at initial fracture are illustrated by the two surfaces delineated in figure 13. These two surfaces coincide at temperatures of −78° C and below, for notch depths of 10 percent or greater, and for all notch depths at −196° C. This coincidence is associated with the fracture of these specimens while the loads were still increasing.

The true stresses at maximum load and at initial fracture increased greatly with decrease in temperature (fig. 13). However, the relative increase in these values with decrease in temperature from +25° to −78° or to −196° C (table 3) is significantly smaller

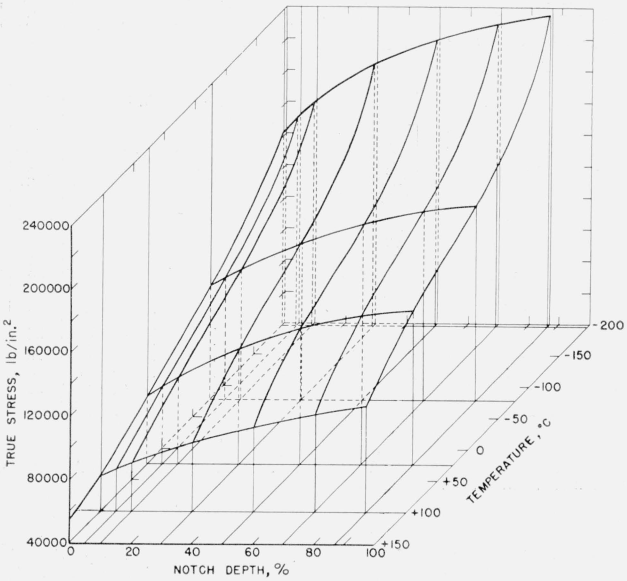

FIGURE 10. *Variation of the true stress at a true strain of 0.02 with notch depth and temperature of the tensile specimens.*

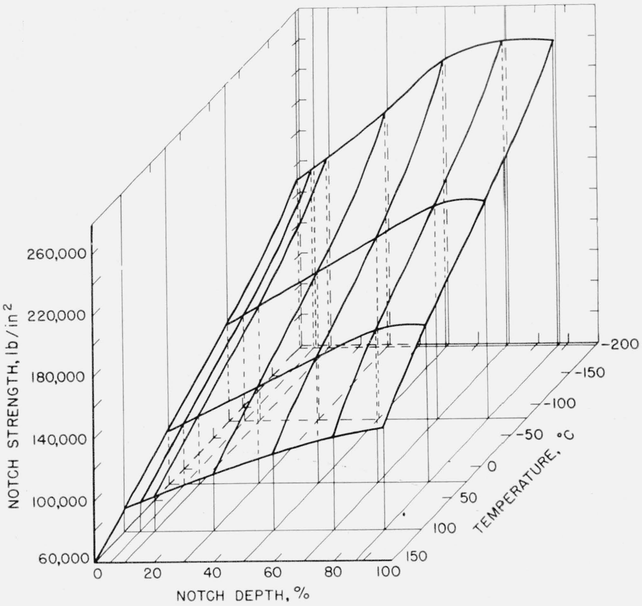

FIGURE 11. *Variation of the notch strength with the notch depth and temperature of the tensile specimens.*

TABLE 2. *Tensile properties at +100°, +25°, −78°, and −196° C of notched specimens (60° notch angle, 0.05-in. root radius) of initially annealed, commercially pure titanium*

Specimen [a] designation	Temperature	Notch depth	D [b]	d [c]	Notch strength [e]	Ratio of notch strength to tensile strength	True stress at—			Ratio of true stress of notched to unnotched specimens at—			True strain [f] at—		Ratio of true strain of notched to unnotched specimens at—		Reduction of area
							True strain of 0.02	Maximum load	Initial fracture	True strain of 0.02	Maximum load	Initial fracture	Maximum load	Initial fracture	Maximum load	Initial fracture	
	°C	*%*	*in.*	*in.*	*lb/in.²*		*lb/in.²*	*lb/in.²*	*lb/in.²*								*%*
G4	+100	5	0.360	0.350	77,000	1.03	65,000	87,000	119,000	1.02	1.02	1.03	0.124	0.631	0.95	0.82	49
G11	+100	10	.370	.350	81,000	1.08	64,000	93,000	121,000	1.01	1.09	1.04	.136	.534	1.05	.69	42
G2	+100	10	.370	.350	82,000	1.09	70,000	94,000	123,000	1.09	1.11	1.06	.132	.522	1.02	.68	40
G3	+100	30	.418	.350	98,000	1.30	83,000	116,000	130,000	1.30	1.36	1.12	.173	.363	1.33	.47	30
G1	+100	50	.495	.350	108,000	1.44	93,000	126,000	142,000	1.46	1.47	1.22	.154	.363	1.19	.47	30
J6	+100	50	.495	.350	109,000	1.45	91,000	129,000	142,000	1.43	1.51	1.22	.162	.332	1.25	.43	28
G5	+100	70	.639	.350	119,000	1.59	100,000	136,000	154,000	1.56	1.59	1.33	.135	.382	1.04	.50	32
J7	+100	70	.639	.350	120,000	1.60	101,000	138,000	154,000	1.58	1.61	1.33	.139	.359	1.07	.47	30
E11	+100	87	.990	.350	125,000	1.67	107,000	143,000	157,000	1.67	1.67	1.35	.135	.318	1.04	.41	29
D14	+25	5	.360	.350	99,000	1.05	92,000	112,000	140,000	1.10	1.05	0.97	.118	.488	0.91	.69	41
D15	+25	10	.370	.350	105,000	1.12	96,000	122,000	141,000	1.14	1.15	.98	.151	.348	1.17	.49	32
G6	+25	10	.370	.350	103 000	1.10	91,000	120,000	139,000	1.08	1.13	.96	.155	.341	1.20	.48	30
F5	+25	10	.370	.350	103,000	1.10	88,000	123,000	144,000	1.05	1.16	1.00	.172	.391	1.33	.55	33
D17	+25	30	.418	.350	125,000	1.33	114,000	146,000	156,000	1.36	1.37	1.08	.151	.226	1.17	.32	20
G12	+25	30	.418	.350	120,000	1.28	104,000	145,000	154,000	1.24	1.36	1.07	.192	.266	1.48	.38	24
F10	+25	30	.418	.350	123,000	1.31	106,000	148,000	156,000	1.26	1.39	1.08	.182	.250	1.41	.35	24
D4	+25	50	.495	.350	141,000	1.50	130,000	159,000	177,000	1.55	1.49	1.23	.122	.256	0.94	.36	23
J5	+25	50	.495	.350	140,000	1.49	120,000	164,000	172,000	1.43	1.54	1.19	.158	.218	1.22	.31	20
F20	+25	50	.495	.350	142,000	1.51	118,000	166,000	174,000	1.40	1.56	1.20	.158	.222	1.22	.31	23
D16	+25	70	.639	.350	162,000	1.72	138,000	183,000	195,000	1.64	1.72	1.35	.122	.207	0.94	.29	21
F21	+25	70	.639	.350	156,000	1.66	126,000	178,000	192,000	1.50	1.67	1.33	.130	.255	1.00	.36	24
D19	+25	87	.990	.350	167,000	1.78	135,000	188,000	198,000	1.61	1.77	1.37	.118	.183	0.91	.26	18
A3	+25	87	.990	.350	155,000	1.65	134,000	180,000	188,000	1.60	1.69	1.30	.146	.216	1.13	.31	20
N6	+25	87	.990	.350	160,000	1.70	132,000	181,000	195,000	1.57	1.70	1.35	.125	.222	0.97	.31	21
I5	−78	5	.360	.350	128,000	1.03	117,000	154,000	162,000	1.04	1.06	0.91	.178	.252	1.11	.48	24
I3	−78	10	.370	.350	134,000	1.08	120,000	164,000	164,000	1.06	1.12	.92	.203	.203	1.27	.39	19
I2	−78	30	.418	.350	156,000	1.26	142,000	(g)	177,000	1.26	----	.99	(g)	.132	----	.25	12
I1	−78	50	.495	.350	177,000	1.43	146,000	(g)	200,000	1.28	----	1.12	(g)	.119	----	.23	10
I4	−78	70	.639	.350	199,000	1.61	153,000	(g)	223,000	1.35	----	1.25	(g)	.115	----	.22	12
A12	−78	87	.990	.350	200,000	1.61	173,000	(g)	217,000	1.53	----	1.21	(g)	.086	----	.17	10
N7	−78	87	.990	.350	200,000	1.61	150,000	(g)	222,000	1.33	----	1.24	(g)	.102	----	.20	10
F1	−196	5	.360	.350	177,000	1.05	169,000	(g)	199,000	1.05	----	0.87	(g)	.118	----	.34	11
F2	−196	10	.370	.350	183,000	1.08	182,000	(g)	199,000	1.13	----	.87	(g)	.081	----	.24	8
F3	−196	30	.418	.350	213,000	1.26	210,000	(g)	221,000	1.31	----	.97	(g)	.039	----	.11	5
F17	−196	50	.495	.350	249,000	1.47	215,000	(g)	263,000	1.34	----	1.15	(g)	.056	----	.16	6
A11	−196	50	.495	.350	243,000	1.44	225,000	(g)	255,000	1.40	----	1.12	(g)	.052	----	.15	6
F4	−196	70	.639	.350	258,000	1.53	230,000	(g)	270,000	1.43	----	1.18	(g)	.046	----	.13	5
A9	−196	87	.990	.350	257,000	1.52	235,000	(g)	266,000	1.46	----	1.17	(g)	.037	----	.11	4
N8	−196	87	.990	.350	256,000	1.52	239,000	(g)	264,000	1.48	----	1.16	(g)	.031	----	.09	4

[a] All specimens prepared from the same bar are designated by the same letter.
[b] Diameter of cylindrical portion of the specimen adjacent to the notch.
[c] Diameter of specimen at the base of the notch.
[e] Determined by dividing the highest load attained by the original minimum cross-sectional area.
[f] Includes elastic and plastic deformation.
[g] Fractured before the slope of the load-extension curves became zero.

TABLE 3. *Effect of test temperature and notch depth on relative values of some strength indices for initially annealed commercially pure titanium*

Notch depth	$\frac{\sigma_{\delta=0.02} \text{ at } T_2}{\sigma_{\delta=0.02} \text{ at } T_1}$				$\frac{\sigma_{\text{Maximum load}} \text{ at } T_2}{\sigma_{\text{Maximum load}} \text{ at } T_1}$				$\frac{\sigma_{\text{fracture}} \text{ at } T_2}{\sigma_{\text{fracture}} \text{ at } T_1}$				$\frac{\text{Notch strength at } T_2}{\text{Notch strength at } T_1}$			
	T_1, ° C----- +25 T_2, ° C----- +100	+25 −78	+25 −196	+100 −196	+25 +100	+25 −78	+25 −196	+100 −196	+25 +100	+25 −78	+25 −196	+100 −196	+25 +100	+25 −78	+25 −196	+100 −196
%																
0	0.76	1.35	1.91	2.53	0.80	1.36	1.87	2.34	0.80	1.24	1.58	1.97	[a] 0.80	[a] 1.32	[a] 1.80	[a] 2.25
5	.71	1.27	1.84	2.60	.78	1.38	1.78	2.29	.85	1.16	1.42	1.67	.78	1.29	1.79	2.30
10	.73	1.31	1.99	2.72	.77	1.35	1.64	2.13	.86	1.16	1.41	1.63	.78	1.29	1.76	2.24
30	.77	1.31	1.94	2.53	.79	(b)	(b)	(b)	.84	1.14	1.42	1.70	.80	1.27	1.73	2.17
50	.75	1.19	1.79	2.39	.78	(b)	(b)	(b)	.81	1.15	1.49	1.82	.77	1.26	1.74	2.27
70	.76	1.16	1.74	2.29	.76	(b)	(b)	(b)	.80	1.15	1.40	1.75	.75	1.25	1.62	2.16
87	.80	1.21	1.77	2.21	.78	(b)	(b)	(b)	.81	1.13	1.37	1.69	.78	1.24	1.59	2.05

[a] Ratio of tensile strengths.
[b] Fractured at −78° and −196° C before the slope of the load-extension curves became zero.

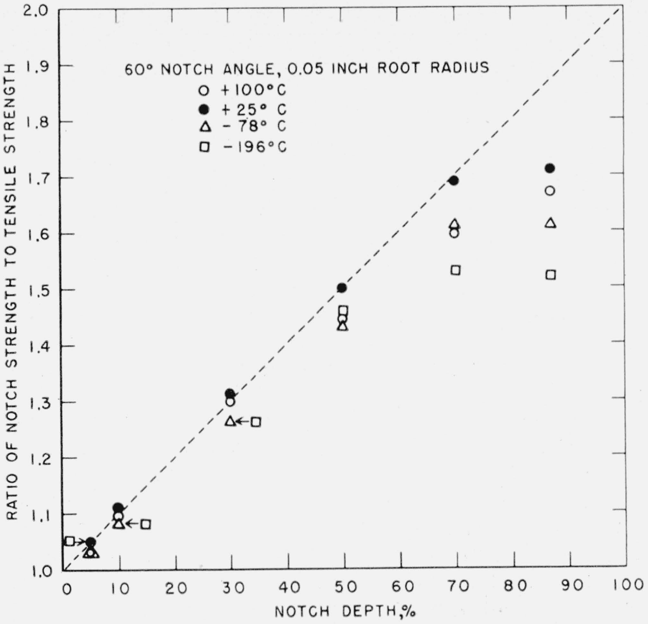

FIGURE 12. *Effect of the notch depth of tensile specimens on the ratio of notch strength to tensile strength.*

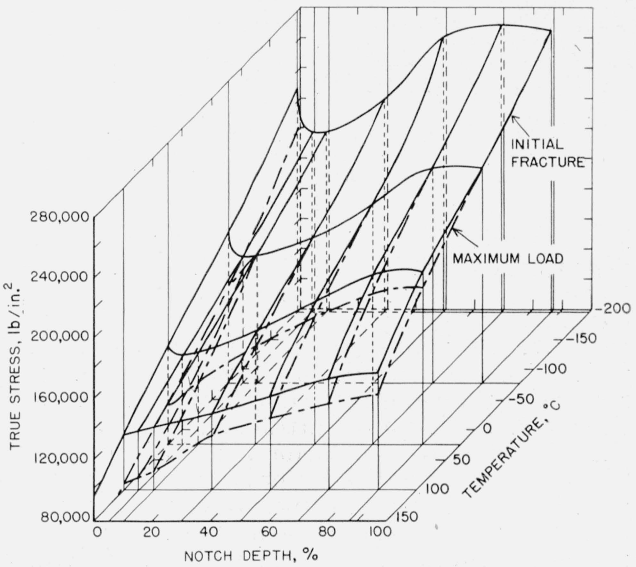

FIGURE 13. *Variation of the true stresses at maximum load and at initial fracture with the notch depth and temperature of tensile specimens.*

than the corresponding relative increase in the 0.02 stress values; this feature can also be attributed mainly to the decrease in ductility of the specimens with decrease in temperature.

The true stress at initial fracture at temperatures of +25° C and below, decreased with increase in notch depth up to 10 percent, then increased with increase in depth through the range of 10 to 70 percent, and thereafter changed only slightly with further increase in depth to 87 percent. The decrease for 5 and 10 percent depths can be attributed directly to the decrease in the true strain at initial fracture associated with the stress concentration at the root of the notch. The decrease in the true stress at fracture due to this factor is greater than the small increase in the true stress associated with the induced triaxiality for these shallow notches. For notch depths of 30 percent and greater, the relative effect of the above two factors is reversed, and the triaxiality is the predominant one, as the stress concentration factor and the ductility of the specimens changed only slightly, whereas the triaxiality and flow stress increased considerably, with the increase in notch depth.

(2) *Ductility.* The effects of temperature and notch depth on the true strains at maximum load and at initial fracture are shown in figure 14. The true strains at maximum load for the specimens that attained a normal maximum load condition did not vary significantly either with temperature or notch depth. A slight, although probably insignificant, maximum is exhibited in the curves showing the effect of notch depth on the true strain at maximum load at temperatures of +25° and +100° C. The true strain at initial fracture decreased continuously with decrease in temperature below +100° C.

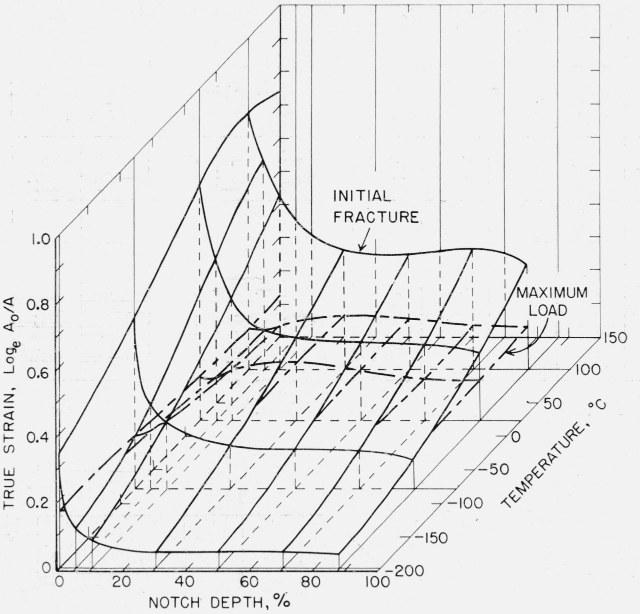

FIGURE 14. *Variation of the true strains at maximum load and at initial fracture with the notch depth and temperature of the tensile specimens.*

Moreover, the true strain at initial fracture decreased very rapidly with increase in notch depth to about 10 percent, less rapidly with increase to 30 percent, changed only slightly with further increase in depths to 50 and 70 percent, and then decreased slightly with increase in depth to 87 percent. The pronounced dependence of the ductility of this metal on the notch depth can be attributed to variations in the stress concentration factor and triaxiality (fig. 9). The stress concentration factor increases very rapidly with increase in notch depth to about 10 percent, and less rapidly with increase in depth from 10 to 30 percent, whereas the triaxiality for these shallow-notched specimens is relatively small. Therefore, it can be postulated that the large decrease in ductility of these titanium specimens (fig. 14) with increase in notch depth to 5, 10, and 30 percent is due mainly to the detrimental effect of the stress concentration and accompanying stress and strain gradients in the region near the base of the notch. The triaxiality of the stress system also reduces the ductility of specimens but its effect for these shallow-notched specimens is relatively small. However, for the deep-notched specimens, the effect of the relatively large triaxiality on the ductility is significant as is shown in figure 14 by an appreciable decrease in the true strain at initial fracture at temperatures of +100°, +25°, and −78° C as the notch depth is increased from 70 to 87 percent; the change in the stress concentration factor with notch depth in this range is very small, and the triaxiality apparently is the predominant factor involved in the initiation of the fracture at these temperatures of the specimens with notch depths of 70 and 87 percent.

Some corroboratory evidence in support of the above views is provided in the photographs of the fracture surfaces of the notched specimens presented in figure 15. The fractures at +100°, +25°, and −78° C of specimens with notch depths of 5, 10, 30, and 50 percent, and the fractures of all the notched specimens at −196° C were initiated at points of high-stress concentration at, or near, the root of the notch. Conversely, the fractures at +100°, +25°, and −78° C of specimens with notch depths of 70 and 87 percent were initiated in the region of high triaxial stresses near the axis. The total deformation of the deep-notched specimens at these temperatures was considerable; it apparently was great enough to reduce the stress concentration near the root of the notch so that the effect of the high triaxial stresses was the predominant factor in the initiation of these fractures. At −196° C, the total deformation of the deep-notched specimens was very small. It was not great enough to reduce, to any significant extent, the stress concentration near the root of the notch, and the stress concentration remained as the predominant factor in the initiation of the fractures.

c. Work Hardening Characteristics

The rate of work hardening,[8] $d\sigma/d\delta$, of the titanium was affected by the temperature and notch depth. This is indicated qualitatively in figures 4 to 8 by an increase in the slopes of the curves at a given true strain with either a decrease in temperature or an increase in notch depth.

The relations observed between the rates of work hardening and true strain of unnotched specimens of the titanium at different temperatures are summarized in figure 16. The rates of work hardening at constant true strains, except at the small true strains in the region of initial yielding, increased continuously with decrease in temperature over the range of +150° to −196° C. The rates of work hardening of the specimens decreased greatly with increase in true strains for strains less than those at the maximum loads. The decrease in the rate of work hardening with increase in strain, above that at maximum load was still considerable at the lower temperatures, but it was very slight at +100° and +150° C.

The effect of notch depth and the accompanying induced triaxiality on the rate of work hardening of the titanium is illustrated quantitatively in figure 17 for the tension tests at +25° C. The rate of work hardening of the metal increased with increase in the notch depth and decreased with increase in true strain; the rate of decrease was relatively small with strains in excess of about 0.3. Similar results (not shown) were observed for the tests at +100°, −78°, and −196° C; however, at −78° and −196° C the true strain range was much smaller due to the limited ductility of the notched specimens at these temperatures. In the tests at +100° C, considerable scatter was observed in the rates of work hardening of the notched specimens at strains

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[8] The rate of work hardening, determined as $d\sigma/d\delta$, at any true strain is the slope of the true stress-true strain curve at that strain. For strains of an unnotched specimen beyond that at maximum load, the increase in the flow stress resulting from the triaxiality induced by the necking of the specimen is included in the value of $d\sigma/d\delta$.

FIGURE 15. *Effect of test temperature and notch depth on the appearance of the fracture surfaces of the tensile specimens.* Photographs, X 2.

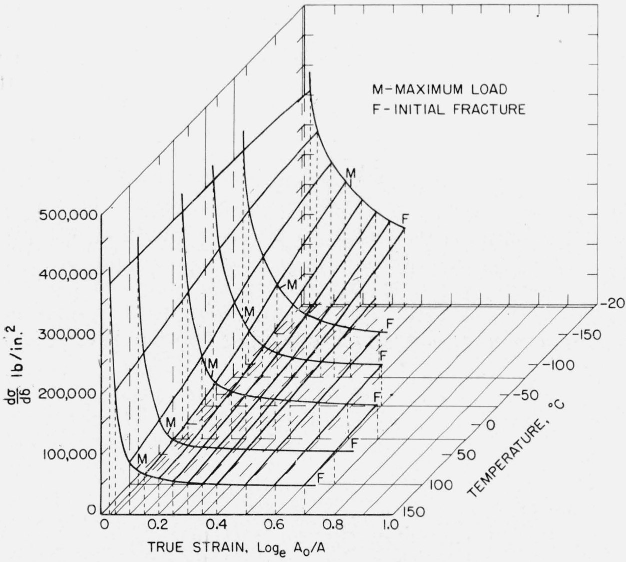

FIGURE 16. *Relation between the rate of work hardening and true strain of unnotched tensile specimens at different temperatures.*

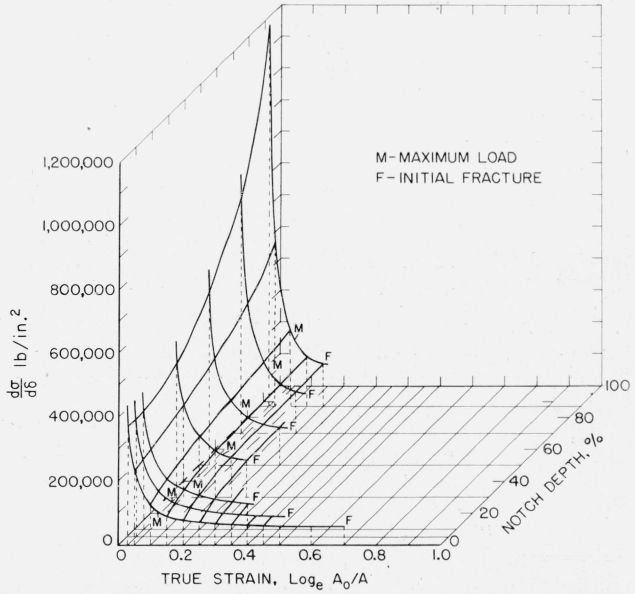

FIGURE 17. *Relation between the rate of work hardening and true strain of tensile specimens of different notch depths at +25° C.*

above that at maximum load, and the effect of notch depth on the rates of work hardening was considerably less than that observed in the tests at +25° C.

The dependence of the rates of work hardening of the titanium on the stress system may be explained by the hypothesis, suggested in a previous paper [10], as follows: Deformation in tension under a multiaxial stress system, such as the triaxial stresses induced in these notched specimens, occurs by the movement of dislocations on a greater number of slip planes within the individual crystals of the polycrystalline specimen than is the case for deformation under uniaxial tension, and more duplex or cross slip will also occur with deformation under the multiaxial stress system. The number of intersections of dislocations, with the accompanying formation of jogs in the dislocations and point defects in the metal, increases with increase in the triaxiality and accompanying increase in cross slip. Energy is required to move one dislocation across another dislocation. Moreover, the energy required to move a dislocation with a jog is greater than that required to move the dislocation prior to the formation of the jog. The point defects formed may also act as barriers to the movement of dislocations. These factors tend to increase the rate of work hardening of the metal [17, 18, 19].

d. Some Effects of Interstitials

Recent investigations [20, 21, 22] have shown that the mechanical properties of high-purity alpha titanium are affected greatly by the interstitial elements (carbon, nitrogen, oxygen, and hydrogen). Carbon, nitrogen, and oxygen strengthen the metal and also tend to decrease its ductility. Hydrogen is generally believed to be one of the main causes of embrittlement of the metal. The main difference in the chemical composition of the present heat of titanium and that of the heat used in the previous study [10] at the Bureau is in the amounts of the interstitial elements; the interstitial contents (percent by weight) of these two heats of the titanium were as follows:

	Carbon	*Oxygen*	*Nitrogen*	*Hydrogen*
Previous heat	0. 02	0. 07	0. 02	0. 006
Present heat	. 04	. 21	. 04	. 012

A comparison of some of the strength and ductility indices of unnotched specimens of the two heats of titanium studied at the Bureau is given in table 4.

The 0.02 stress at +100°, +25°, −78°, and −196° C (table 4) of the present heat of titanium ranged from 12 to 30 percent greater than that of the previous heat of titanium with its lower interstitial contents. It may be postulated that this difference in the 0.02 stress values of the two heats is due mainly to the greater density of "Cottrell clouds" (clusters of interstitial atoms around the dislocations) [17] in the annealed metal with the higher interstitial contents; more energy is required for the initiation of the movement of a dislocation with a surrounding cluster of interstitial atoms than for that of a similar dislocation not partially anchored by interstitial atoms. The binding effect of the surrounding interstitial atoms on a dislocation increases with decrease in the rates of diffusion of the interstitial atoms such as accompanies a decrease in temperature of the metal. This feature is indicated in table 4 by the significantly higher ratio of the 0.02 stresses at −196° and +25° C, respectively, for the present heat of titanium with its higher interstitial contents.

Table 4. *Some comparative strength and ductility values of the unnotched tensile specimens of the present and previous heats [10] of initially annealed, commercially pure titanium*

Temperature		+100° C	+25° C	−78° C	−196° C
Ratio of true stress at a true strain of 0.02 for the present heat to that for the previous heat		1. 12	1. 22	1. 27	1. 30
Ratio of true stress at a true strain of 0.15 to that at 0.02	Present heat	1. 32	1. 30	1. 27	1. 26
	Previous heat	1. 31	1. 32	1. 31	1. 29
Ratio of true strain at initial fracture for the present heat to that for the previous heat		1. 25	1. 03	0. 70	0. 44
Ratio of true stress at a true strain of 0.02 at −196° to that at +25° C		Present heat 1. 90 Previous heat 1. 75			

The interstitial atoms also greatly affect the resistance of the metal to the continued movement of dislocations and thus affects its work hardening characteristics. Evidence of this effect is provided indirectly in table 4 by the ratios of the true stresses at true strains of 0.15 and 0.02, respectively, for these two heats of titanium.[9] These ratios, which may be considered as measures of the relative work hardening during this range of deformation, are nearly the same for both heats of the metal. However, as the 0.02 stress was greater for the heat with the higher interstitial contents, the increase in the resistance to flow during the deformation of these specimens was greater than that of specimens of the other heat of titanium. The slight increase exhibited in these ratios for both heats of titanium as the temperature was increased may also be interpreted as indirect evidence of slip along more prismatic planes, and including some pyramidal planes and possibly basal planes at the higher temperatures. This would be accompanied by an increase in the amount of cross slip and the number of intersections of dislocations, thereby increasing the work hardening of the metal.

The effect of the interstitials on the embrittlement of the titanium at low temperatures is indicated in table 4 by the ratios of the true strain at initial fracture of the specimens. The ductility at room temperature of specimens of both heats was about the same. However, the low temperature embrittlement of the titanium by the interstitials was very pronounced as shown by the large decrease in these ratios as the temperature was lowered to −78° and −196° C.

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[9] The upper range of the strain for these ratios was limited to 0.15 in order to eliminate any effects that might be attributed to triaxiality accompanying the necking of the specimens.

4. Summary and Conclusions

A study was made of the behavior at low temperatures of unnotched and notched tensile specimens (60° notch angle, 0.05-in. root radius, 0.35-in. diameter at root of notch, and selected notch depths) and Charpy V-notch impact specimens of a heat of annealed commercially pure titanium.

The transition from ductile to brittle behavior in the Charpy impact tests occurred within the range of +125° to +80° C; only a small amount of notch toughness (3 to 4 ft-lb energy absorbed) was retained by the metal at −196° C.

The resistance to deformation of unnotched and notched tensile specimens increased continuously as the temperature was lowered within the range of +150° to −196° C. The strength of the titanium was also affected greatly by the stress system induced by a notch; strength indices, such as true stress at a true strain of 0.02 notch strength, and true stresses at maximum load and at initial fracture, increased greatly with increase in the induced triaxiality accompanying an increase in the notch depth.

The ability of the titanium to deform under uniaxial stress apparently was not affected greatly by lowering of temperature, as the true strain at maximum load in the tension tests on unnotched specimens increased only slightly as the temperature was lowered within the range of +150° to —196° C.

The ductility of the titanium under multiaxial stresses, however, was very dependent on temperature. The true strain at initial fracture of notched specimens of constant notch depth decreased continuously with lowering of temperature. Moreover, the ductility of notched specimens decreased very rapidly at all test temperatures with increase in notch depth to 10 percent, decreased less rapidly with increase in depth to 30 percent, changed very little with further increase in depth to 70 percent and then decreased slightly with increase in depth to 87 percent. The stress concentration factor increases very rapidly with increase in notch depth to about 10 percent, less rapidly with increase in depth from 10 to 30 percent, and then rather slowly with further increase in notch depth, whereas, the induced triaxiality is relatively small for the shallow-notched specimens but increases to a fairly large value for the deep notch specimens. Thus, it may be concluded that the decrease in tensile ductility of the notched specimens apparently depends mainly on the stress and strain gradients accompanying the stress concentration near the root of the notch, and only to a minor extent, except perhaps for very deep notches, on the induced triaxiality. This conclusion, however, should be considered as tentative, as the change in notch geometry in this study was limited to a variation of the notch depth of notches with constant notch angle, root radius, and minimum diameter at the root of the notch. Additional experimental data involving other variations in the geometry of the notch, such as notch angle and root radius, are needed to definitely establish the relative effect of the stress concentration factor and triaxiality on the ductility of the titanium.

The rates of work hardening of the titanium specimens under tension depended on the temperature and the stress system; the rate of work hardening increased with decrease in temperature and with increase in the triaxiality of the stress system.

A comparison of the tensile data obtained previously on another heat of annealed commercially pure titanium of low interstitial contents, with those obtained in the present investigation shows that the strength and work hardening increase and the ductility at temperatures below +25° C decreases with increase in the interstitial contents of titanium.

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