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Compatibility of Zircaloy-4 and Nb-1 Wt% Zr Alloy in Hydrogen As a Function of Temperature

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COMPATIBILITY OF ZIRCALOY-4 AND Nb-1 WT% Zr ALLOY IN HYDROGEN AS A FUNCTION OF TEMPERATURE

by

R. E. Riley and T. I. Jones

ABSTRACT

The susceptibility of zirconium- and niobium-base alloys to hydrogen embrittlement is well known. However, little is known about the compatibility of these materials when exposed to a hydrogen atmosphere at moderately elevated temperatures. This report presents evidence that Zircaloy-4 and Nb-1 wt% Zr alloys exhibit a reasonable time-temperature-hydrogen compatibility range before catastrophic embrittlement occurs.

I. INTRODUCTION

Zirconium- and niobium-base alloys have been considered structural materials for short-term service in a hydrogen atmosphere at moderately elevated temperatures. Because present literature revealed no data on the mechanical (tensile) properties or microstructure of these materials under these conditions, we decided to study the effect of time-temperature exposure of these alloys in a hydrogen atmosphere. The two materials selected for this study were Zircaloy-4 and Nb-1 wt% Zr alloys.

1						12						18				29					40
2	3	4	5	6								19				30	31	32	33	34	41
												20									42
												21									43
												22									44
												23									45
7	8	9	10	11	13	14	15	16	17			24				35	36	37	38	39	46
												25									47
												26									48
												27									49
												28									50

Fig. 1.
Typical layout for sampling sheet stock.

II. SPECIMEN PREPARATION

Sheet stock, ~0.020 in. thick, of both materials was cut into 1-in.-wide by 5-in.-long pieces suitable for blanking into tensile specimens. A typical layout for sectioning 25 longitudinal and 25 transverse blanks from the sheet is shown in Fig. 1.

The blanked tensile specimens were marked with a suitable series of letters and numbers designating the type of material, sheet number, orientation, and time and temperature of hydrogen exposure. The Los Alamos Scientific Laboratory's (LASL) Analytical Chemistry Group (CMB-1) analyzed samples of the as-received

material for hydrogen, oxygen, and nitrogen, as well as for major and minor elements.

Three specimens from each sheet and three each of the longitudinal and transverse blanks were tested at room temperature for quality control of the as-received material. The remaining specimens were cleaned to remove dirt and grease, and then were stored in an evacuated desiccator until they were needed for further treatment. The cleaned specimens were handled with clean white cotton gloves at all stages of processing and were weighed and measured just before hydrogen-exposure treatments.

III. SCHEDULE FOR TENSILE SPECIMEN HYDROGEN EXPOSURE

The hydrogen-exposure treatments for the Zircaloy-4 and Nb-1 wt% Zr alloy sheet specimens are presented in Tables I and II, respectively. For any particular hydrogen treatment, the furnace (Figs. 2 and 3) was evacuated, heated to the desired temperature, hydrogen gas admitted at a flow rate of 10 cfh and 600 torr, and, after the designated time, the hydrogen gas was shut off, argon gas admitted, and the furnace turned off and allowed to cool overnight. All specimens received their designated time at temperature in one run; no interruption of the specific treatment was planned or encountered.

After hydrogen treatment, the specimens were weighed and then were tension tested at room temperature, using standard ASTM test procedures, for ultimate tensile strength, 0.2% offset yield strength, elongation, and diamond pyramid hardness (DPH). The blanking scrap from the tensile specimens was heat treated with the specimens. Two of the blanks from each series of triplicate specimen were used for chemical and gas analysis and the third was used for metallography and hardness analyses. The tensile specimens were similarly analyzed for hydrogen by weight.

Fig. 3.
Schematic of hydriding furnace.

IV. ANALYTIC RESULTS

The analytical results for the Zircaloy-4 and Nb-1 wt% Zr alloys are presented in Tables III and IV, respectively. Generally, the hydrogen weight and chemical analyses did not agree for the Zircaloy-4 specimens. Hydrogen contents determined by weight were erratic, apparently due to outgassing and possible loss of some elemental components by vaporization. This was evidenced by the presence of a dark metallic-like coating in the cooling zone of the furnace after each run, particularly for the higher temperatures and/or longer runs. Therefore, it seems that the hydrogen content obtained from chemical analysis is always the more reliable figure. The Zircaloy-4 hydrogen content (by chemistry) vs heat-treat temperature and time plot (Fig. 4) shows that at low temperatures and short times some samples gained and some samples decreased in hydrogen content. However, for exposure times of 4 h or longer, all samples showed continual increase in hydrogen content.

Generally, the hydrogen weight of the Nb-1 wt% Zr alloy specimens agreed with the chemical analyses. Some samples exposed at 200°F and 400°F lost weight due to outgassing in the vacuum part of the run, and little or no hydrogen take-up during the hydrogen part of the run. The first samples exposed at 800°F were unsuitable for

Fig. 2.
Hydriding furnace.

Fig. 4.

Effect of time at temperature on hydrogen pickup in Zircaloy-4.

tensile tests because of warping; consequently, no additional samples were treated at this temperature. A plot of the hydrogen adsorption data for the Nb-1 wt% Zr alloy is presented in Fig. 5. The data show that the Nb-1 wt% Zr alloys do not pick up hydrogen until a temperature over 400°F has been reached for times up to 2 h.

V. TENSILE RESULTS

The hydrogen-exposed and the as-received tensile specimens were tested at room temperature using the standard ASTM procedure for sheet specimens. The ultimate tensile strength, 0.2% offset yield strength, percent elongation in 1/4, 1/2, and 1 in., and hardnesses are presented in Tables V and VI for the Zircaloy-4 and Nb-1 wt% Zr alloys, respectively.

Table V shows the Zircaloy-4 sheet material to be nearly isotropic. With one exception, there was no appreciable strengthening of the hydrogen-exposed specimens. The specimens heated in hydrogen at 400°F for 4 h were stronger than the specimens exposed for longer or shorter times at this temperature. The strength did tend to decrease slightly after the 600°F-8-h hydrogen treatment. The percent elongation remained constant up through the 600°F-4-h hydrogen treatment. A decrease in percent elongation was observed in the specimens exposed at 600°F for 8 h in hydrogen.

Metallographic examinations were made on one specimen from each condition. In general, the microstructures showed no grain growth or evidence of hydride formation, with the exception of the specimens heated in

Fig. 5.

Effect of time at temperature on hydrogen pickup in Nb-1 wt% Zr alloy.

hydrogen at 500°F for 1 h and 600°F for 8 h. These specimens showed only a slight, discontinuous surface hydride. Figures 6a and 6b are typical microstructures for all specimens; Figs. 6c and 6d are typical of the surface hydride observed on the samples mentioned above.

The Nb-1 wt% Zr alloy specimens (Table VI) show this sheet material to be isotropic. The strength values, particularly ultimate tensile strength, show an increase with increasing severity of hydrogen exposure above 400°F. The gross increase in strength of the specimens exposed at 600°F for 1/2 h in hydrogen was ~26%. Longer exposure at this temperature resulted in slightly lower strengths, probably because of hydrogen embrittlement. The tensile elongation remained fairly constant up to the embrittling times of 1 and 2 h at 600°F in hydrogen.

One specimen from each time-temperature heat treatment was examined metallographically. A few were chosen to represent typical structures. The typical structure observed for most of the specimens is shown in Fig. 7a. Figure 7b shows hydride platelets in the transverse specimen that were held at 600°F for 1 h in hydrogen. We have no explanation as to why the platelets were observed in the transverse specimen and not in the longitudinal

a. Bright Field (500X).

b. Polarized Light (250X).

Sample Z-101, 34 ppm, H₂.

c. Bright Field (500X).

Sample Z-204, 55 ppm.

d. Bright Field (500X).

Sample Z-251, 50 ppm.

Fig. 6.
Typical microstructures for the Zircaloy-4 specimens.

a. Sample N-101, <5 ppm, H₂.

b. Sample N-210, 730 ppm, H₂.

c. Sample N-220, 1300 ppm, H₂.

d. Sample N-233, 2700 ppm, H₂.

Fig. 7.
Typical microstructures for the Nb-1 wt% Zr alloy specimens (250X).

specimen. The 2-h exposure at 600°F showed the same effect. Figures 7c and 7d show the hydride platelets in the longitudinal and transverse tensile specimens exposed at 800°F for 1/2 h in hydrogen. These specimens had 1300- and 2700-ppm hydrogen, respectively. As mentioned previously, these specimens were badly warped and tensile data were not obtained. However, the hardness remained constant at 125 DPH. The overall increase in hardness of ~25% was similar to the maximum strength increase.

The Nb-1 wt% Zr alloy sheet was a more uniform starting material. The Zircaloy-4 should have been, but was not, vacuum annealed to remove the residual hydrogen in the starting material. There is little doubt that this partly accounted for this material's abnormal behavior on subsequent hydrogen exposures. Nevertheless, both materials have reasonable time-temperature-hydrogen compatibility range.

VI. CONCLUSIONS

The range of time-temperature compatibility of Zircaloy-4 and Nb-1 wt% Zr alloys in a hydrogen atmosphere was somewhat surprising. The Zircaloy-4 specimens showed essentially no evidence of significant hydrogen pickup until times of 8 h at 500°F and 4 h at 600°F. There was no embrittlement, as evidenced by loss in

ductility, until a time of 8 h at 600°F in hydrogen. The samples exposed at 800°F were badly warped and were not tension tested. However, it is assumed that they were quite brittle because of the amount of hydrogen pickup (1300- and 2700-ppm hydrogen) for the two specimens analyzed. The Zircaloy-4 material should have been vacuum annealed before the hydrogen-exposure treatments, but the observed trends are real and there is no reason to repeat the experiment.

The Nb-1 wt% Zr alloy sheet was a more uniform material than the Zircaloy-4 sheet and the data observed were good. There was no evidence of hydrogen pickup for times up to 1 h at 400°F. Beyond this time and temperature there was a gradual increase of hydrogen pickup with time at temperature. There was no evidence of embrittlement as indicated by tensile ductility until 1 h at 600°F in hydrogen. At this condition, the loss in ductility was drastic. In general, metallographic results seemed to relate the hydrogen content and the tensile properties.

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TABLE I

HYDROGEN EXPOSURE SCHEDULE
FOR ZIRCALOY-4 SPECIMENS

Specimen Number	Orien- tation	Hydrogen Treatment
Z101, Z128, Z140	L	None
Z102, Z117, Z134	T	None
Z141, Z142, Z143	L	300°F, 1 h
Z103, Z104, Z105	T	300°F, 1 h
Z144, Z145, Z146	L	300°F, 2 h
Z106, Z107, Z108	T	300°F, 2 h
Z147, Z148, Z149	L	300°F, 4 h
Z109, Z110, Z111	T	300°F, 4 h
Z150, Z118, Z119	L	300°F, 8 h
Z130, Z131, Z132	T	300°F, 8 h
Z120, Z121, Z122	L	400°F, 1 h
Z133, Z135, Z136	T	400°F, 1 h
Z123, Z124, Z125	L	400°F, 2 h
Z137, Z138, Z139	T	400°F, 2 h
Z126, Z127, Z112	L	400°F, 4 h
Z113, Z114, Z115	T	400°F, 4 h
Z129, Z156, Z157	L	400°F, 8 h
Z116, Z151, Z152	T	400°F, 8 h
Z201, Z228, Z240	L	None
Z202, Z217, Z234	T	None
Z241, Z242, Z243	L	500°F, 1 h
Z203, Z204, Z205	T	500°F, 1 h
Z244, Z245, Z246	L	500°F, 2 h
Z206, Z207, Z208	T	500°F, 2 h
Z247, Z248, Z249	L	500°F, 4 h
Z209, Z210, Z211	T	500°F, 4 h
Z250, Z218, Z219	L	500°F, 8 h
Z230, Z231, Z232	T	500°F, 8 h
Z220, Z221, Z222	L	600°F, 1 h
Z233, Z235, Z236	T	600°F, 1 h
Z223, Z224, Z225	L	600°F, 2 h
Z237, Z238, Z239	T	600°F, 2 h
Z226, Z227, Z212	L	600°F, 4 h
Z213, Z214, Z215	T	600°F, 4 h
Z229, Z256, Z257	L	600°F, 8 h
Z216, Z251, Z252	T	600°F, 8 h

TABLE II

HYDROGEN EXPOSURE SCHEDULE FOR
Nb-1 WT% Zr ALLOY SPECIMENS

Specimen Number	Orien- tation	Hydrogen Treatment
N101, N128, N140	L	None
N102, N117, N134	T	None
N141, N142, N143	L	None
N103, N104, N105	T	None
N144, N145, N146	L	200°F, 1/2 h
N106, N107, N108	T	200°F, 1/2 h
N147, N148, N149	L	200°F, 1 h
N109, N110, N111	T	200°F, 1 h
N150, N118, N119	L	200°F, 2 h
N130, N131, N132	T	200°F, 2 h
N120, N121, N122	L	400°F, 1/2 h
N133, N135, N136	T	400°F, 1/2 h
N123, N124, N125	L	400°F, 1 h
N137, N138, N139	T	400°F, 1 h
N126, N127, N112	L	400°F, 2 h
N113, N114, N115	T	400°F, 2 h
N201, N228, N240	L	None
N202, N217, N234	T	None
N241, N242, N243	L	None
N203, N204, N205	T	None
N244, N245, N246	L	600°F, 1/2 h
N206, N207, N208	T	600°F, 1/2 h
N247, N248, N249	L	600°F, 1 h
N209, N210, N211	T	600°F, 1 h
N250, N218, N219	L	600°F, 2 h
N230, N231, N232	T	600°F, 2 h
N220, N221, N222	L	800°F, 1/2 h
N233, N235, N236	T	800°F, 1/2 h
N223, N224, N225	L	800°F, 1 h
N237, N238, N239	T	800°F, 1 h
N226, N227, N212	L	800°F, 2 h
N213, N214, N215	T	800°F, 2 h

TABLE III
ANALYTICAL RESULTS OF ZIRCALOY-4 SPECIMENS

Sample	Hydriding Conditions		Blanking Scrap Chemistry				Tensile Specimen
	Temp (°F)	Time (h)	O ₂ (ppm)	N ₂ (ppm)	H ₂ (ppm)	H ₂ by wt (ppm)	H ₂ by wt (ppm)
Z101	Control	0		37	60		
Z102	Control	0	730	42	60		
Z117	Control	0		41	20		
Z128	Control	0		42	35		
Z201	Control	0	1200	38	25		
Z202	Control	0		41	25		
Z217	Control	0		37	25		
Z228	Control	0		39	20		
Average			965	40	34		
Z103	300	1				12	18
Z104				42	35	6	9
Z105						24	0
Z141			1100	40	40	80	63
Z142						6	-
Z143						23	0
Average			1100	41	37	25	15
Z106	300	2				12	0
Z107			820	40	40	6	0
Z108						16	18
Z144				40	30	6	9
Z145						0	9
Z146						17	27
Average			820	40	35	10	10
Z109	300	4				-	-
Z110				42	10	-	-
Z111						-	-
Z147			860	40	30	-	8
Z148						-	-
Z149						-	0
Average			860	41	20	-	-
Z118	300	8				-	-
Z119						-	-
Z130						-	0
Z131				36	40	-	-
Z132						-	18
Z150				45	30	-	-
Average				40	35	-	3

TABLE III (cont)

Sample	Hydriding Conditions		Blanking Scrap Chemistry				Tensile Specimen
	Temp (°F)	Time (h)	O ₂ (ppm)	N ₂ (ppm)	H ₂ (ppm)	H ₂ by wt (ppm)	H ₂ by wt (ppm)
Z120	400	1	800	43	35	12	0
Z121						0	—
Z122						—	—
Z133			710	39	50	0	—
Z135						—	—
Z136						—	—
Average			755	41	42	1	—
Z123	400	2		41	15	0	18
Z124						18	18
Z125						12	9
Z137				40	40	12	9
Z138						0	17
Z139						6	9
Average				40	27	8	13
Z112	400	4				24	—
Z113						12	0
Z114			900	35	45	0	0
Z115						—	—
Z126				40	25	19	—
Z127						6	9
Average			900	37	35	11	1
Z116	400	8				30	9
Z129						44	18
Z151			1300	42	60	25	36
Z152			1100	36	40	25	18
Z156						6	18
Z157						23	18
Average			1200	39	50	26	20
Z203	500	1				0	18
Z204						—	27
Z205						—	36
Z241			1000	35	40	6	18
Z242						—	27
Z243						18	18
Average			1000	37	47	4	24
Z206	500	2				12	9
Z207						0	127
Z208						0	45
Z244				38	25	18	9
Z245						12	9
Z246						6	0
Average			1000	40	27	8	12

TABLE III (cont)

Sample	Hydriding Conditions		Blanking Scrap Chemistry				Tensile Specimen
	Temp (°F)	Time (h)	O ₂ (ppm)	N ₂ (ppm)	H ₂ (ppm)	H ₂ by wt (ppm)	H ₂ by wt (ppm)
Z209	500	4				25	9
Z210				43	55	12	9
Z211						12	9
Z247			1100	37	30	--	0
Z248						0	0
Z249						6	9
Average			1100	40	42	9	6
Z218	500	8				67	73
Z219						61	36
Z230						54	55
Z231				40	60	55	36
Z232						66	64
Z250				40	45	75	55
Average				40	52	63	53
Z220	600	1	980	39	30	12	36
Z221						12	27
Z222						18	36
Z233						18	18
Z235			1000	45	5	13	9
Z236						19	9
Average			990	42	17	15	23
Z223	600	2		43	40	44	27
Z224						31	27
Z225						--	0
Z237						31	109
Z238				42	30	31	18
Z239						19	18
Average				42	35	26	33
Z212	600	4				106	18
Z213						65	82
Z214			1800	39	65	77	91
Z215						53	73
Z226			840	41	50	50	55
Z227						63	73
Average			1320	40	57	69	65
Z216	600	8				--	0
Z229			980	38	80	--	--
Z251			1100	39	50	--	--
Z252						--	--
Z256						--	--
Z257						--	--
Average			1040	38	65	--	--

TABLE IV
ANALYTICAL RESULTS OF Nb-1 WT% Zr ALLOY SPECIMENS

Sample	Hydriding Conditions		Blanking Scrap		Tensile Specimen
	Temp (°F)	Time (h)	H ₂ Content by wt (ppm)	H ₂ Content by Chemistry (ppm)	H ₂ Content by wt (ppm)
N101	None	Control		5	
N102		Control		5	
N117		Control		5	
N128		Control		5	
N201		Control		5	
N202		Control		5	
N217		Control		5	
N228		Control		5	
Average				5	
N144	200	1/2	0		0
N145	200	1/2	0	10	0
N146	200	1/2	0		0
N106	200	1/2	0	10	0
N107	200	1/2	0		0
N108	200	1/2	0		0
Average			0	10	0
N147	200	1	12		0
N148	200	1	21		17
N149	200	1	0	10	33
N109	200	1	22		—
N110	200	1	22	10	0
N111	200	1	0		17
Average			12.8	10	13.4
N150	200	2			0
N118	200	2	0	20	17
N119	200	2	0		0
N130	200	2	0		0
N131	200	2	0		67
N132	200	2	0	20	50
Average			0	20	22.3
N120	400	1/2	0		0
N121	400	1/2	0	10	0
N122	400	1/2	0		0
N133	400	1/2	0		0
N135	400	1/2	0	10	0
N136	400	1/2	0		0
Average			0	10	0

TABLE IV (cont)

Sample	Hydriding Conditions		Blanking Scrap		Tensile Specimen
	Temp (°F)	Time (h)	H ₂ Content by wt (ppm)	H ₂ Content by Chemistry (ppm)	H ₂ Content by wt (ppm)
N123	400	1	0		0
N124	400	1	0	20	0
N125	400	1	0		0
N137	400	1	0	20	0
N138	400	1	0		0
N139	400	1	0		0
Average			0	20	0
N126	400	2	0	20	33
N127	400	2	0		17
N112	400	2	11		34
N113	400	2	37		-
N114	400	2	11	20	34
N115	400	2	22		34
Average			13.5	20	30
N244	600	1/2	96		100
N245	600	1/2	95	80	67
N246	600	1/2	99		100
N206	600	1/2	118		118
N207	600	1/2	76	60	102
N208	600	1/2	122		136
Average			101	70	104
N247	600	1	785		702
N248	600	1	809	790	787
N249	600	1	815		723
N209	600	1	851	850	816
N210	600	1	763		730
N211	600	1	711		645
Average			789	820	734
N250	600	2			473
N218	600	2	348		354
N219	600	2	457	460	438
N230	600	2	574		571
N231	600	2	589		606
N232	600	2	459	580	554
Average			485	520	499

TABLE IV (cont)

Sample	Hydriding Conditions		Blanking Scrap		Tensile Specimen
	Temp (°F)	Time (h)	H ₂ Content by wt (ppm)	H ₂ Content by Chemistry (ppm)	H ₂ Content by wt (ppm)
N220	800	1/2	3060		1300 warped
N221	800	1/2	3380		1800 warped
N222	800	1/2	3430		1700 warped
N233	800	1/2	4060		2700 warped
N235	800	1/2	3780		2500 warped
N236	800	1/2	3800		3000 warped
Average			3585		2167

TABLE V
TENSILE PROPERTIES OF HYDROGEN-EXPOSED ZIRCALOY-4

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
Z101	L	None	63.2	50.6	76	54	36	153
Z128	L	None	63.5	52.6	74	53	35	
Z140	L	None	63.3	47.6	74	53	35	
Z201	L	None	64.1	53.0	78	55	36	
Z228	L	None	64.8	52.5	72	51	34	
Z240	L	None	64.3	52.1	76	54	35	156
Average			63.9	51.4	75	53	35	154
Z102	T	None	62.9	52.6	78	58	36	160
Z117	T	None	61.0	50.5	76	54	36	
Z134	T	None	61.8	50.8	74	54	35	
Z202	T	None	63.5	53.0	74	54	36	
Z217	T	None	63.9	53.2	72	51	34	
Z234	T	None	63.2	52.6	82	58	38	160
Average			62.7	52.1	76	55	36	
Z141	L	300°F, 1 h	61.6	51.4	78	51	33	157
Z142	L	300°F, 1 h	61.3	49.3	70	50	33	
Z143	L	300°F, 1 h	60.8	50.3	74	54	35	
Average			61.2	50.0	74	52	34	
Z103	T	300°F, 1 h	59.6	47.8	72	54	36	157
Z104	T	300°F, 1 h	63.6	51.7	72	54	35	
Z105	T	300°F, 1 h	63.3	52.7	78	56	36	
Average			62.2	50.7	74	55	36	
Z144	L	300°F, 2 h	64.2	52.5	76	54	35	157
Z145	L	300°F, 2 h	64.3	52.1	74	53	35	
Z146	L	300°F, 2 h	63.6	52.7	66	49	33	
Average			64.0	52.4	72	52	34	
Z106	T	300°F, 2 h	62.4	52.5	76	55	36	157
Z107	T	300°F, 2 h	62.2	51.6	76	54	35	
Z108	T	300°F, 2 h	62.3	51.2	68	50	33	
Average			62.3	51.8	73	53	35	
Z147	L	300°F, 4 h	62.7	51.0	72	53	34	157
Z148	L	300°F, 4 h	62.4	51.1	68	50	33	
Z149	L	300°F, 4 h	63.1	51.7	76	54	34	
Average			62.7	51.3	72	52	34	
Z109	T	300°F, 4 h	62.3	51.8	70	50	33	157
Z110	T	300°F, 4 h	63.0	53.5	68	50	34	
Z111	T	300°F, 4 h	62.9	52.3	72	52	34	
Average			62.7	52.5	70	51	34	

TABLE V (cont)

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
Z150	L	300°F, 8 h	62.9	50.2	68	49	32	157
Z118	L	300°F, 8 h	63.2	50.3	72	53	34	
Z119	L	300°F, 8 h	63.7	51.8	72	50	33	
Average			63.3	50.8	71	51	33	157
Z130	T	300°F, 8 h	63.2	51.3	74	53	34	
Z131	T	300°F, 8 h	63.0	52.3	74	53	36	
Z132	T	300°F, 8 h	63.4	53.5	72	53	35	
Average			63.2	52.4	73	53	35	
Z120	L	400°F, 1 h	64.4	51.7	66	48	32	
Z121	L	400°F, 1 h	63.5	52.9	62	47	32	
Z122	L	400°F, 1 h	63.8	51.0	74	53	35	
Average			63.9	51.8	67	49	33	
Z133	T	400°F, 1 h	63.0	52.5	74	54	36	
Z135	T	400°F, 1 h	63.2	50.7	72	51	34	
Z136	T	400°F, 1 h	63.0	52.7	76	55	36	
Average			63.1	52.0	74	53	36	
Z123	L	400°F, 2 h	63.6	52.4	74	53	35	
Z124	L	400°F, 2 h	63.7	50.9	74	54	35	
Z125	L	400°F, 2 h	63.5	51.6	72	50	32	
Average			63.6	51.6	73	52	34	
Z137	T	400°F, 2 h	62.8	50.6	78	57	36	
Z138	T	400°F, 2 h	62.9	52.0	78	55	36	
Z139	T	400°F, 2 h	65.1	54.5	70	52	34	
Average			63.6	52.4	75	55	36	
Z126	L	400°F, 4 h	67.0	55.2	70	50	33	
Z127	L	400°F, 4 h	67.2	55.3	72	52	34	
Z112	L	400°F, 4 h	66.3	53.4	72	51	34	
Average			66.8	54.6	71	51	34	
Z113	T	400°F, 4 h	63.0	52.9	74	53	34	156
Z114	T	400°F, 4 h	63.2	52.1	70	53	35	
Z115	T	400°F, 4 h	63.2	51.2	74	52	34	
Average			63.1	52.1	73	53	34	156
Z129	L	400°F, 8 h	62.9	51.3	74	51	34	
Z156	L	400°F, 8 h	63.0	51.9	76	54	36	
Z157	L	400°F, 8 h	62.3	48.9	74	53	34	
Average			62.7	50.7	75	53	35	
Z116	T	800°F, 8 h	61.6	50.1	76	54	36	
Z151	T	800°F, 8 h	61.5	51.2	76	54	35	
Z152	T	800°F, 8 h	60.9	51.3	76	54	36	
Average			61.3	50.9	76	54	36	

TABLE V (cont)

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
Z241	L	500°F, 1 h	63.7	51.6	76	53	35	
Z242	L	500°F, 1 h	64.3	53.2	74	52	34	
Z243	L	500°F, 1 h	63.8	50.4	68	49	33	
Average			63.9	51.7	73	51	34	
Z203	T	500°F, 1 h	63.0	51.5	74	54	36	
Z204	T	500°F, 1 h	62.4	52.1	78	55	36	
Z205	T	500°F, 1 h	62.4	53.5	76	54	35	
Average			62.6	52.4	76	54	36	
Z244	L	500°F, 2 h	63.2	50.9	70	50	34	
Z245	L	500°F, 2 h	63.2	51.0	72	51	34	
Z246	L	500°F, 2 h	61.9	51.7	72	51	34	
Average			62.8	51.2	71	51	34	
Z206	T	500°F, 2 h	60.9	51.6	76	55	35	
Z207	T	500°F, 2 h	60.5	50.4	74	54	35	
Z208	T	500°F, 2 h	61.0	52.6	76	54	35	
Average			60.8	51.5	75	54	35	
Z247	L	500°F, 4 h	61.0	48.8	68	50	34	
Z248	L	500°F, 4 h	60.8	49.2	68	50	34	
Z249	L	500°F, 4 h	60.9	48.9	72	51	34	
Average			60.9	49.0	69	50	34	
Z209	T	500°F, 4 h	63.5	53.8	80	56	36	
Z210	T	500°F, 4 h	63.4	52.6	80	56	37	
Z211	T	500°F, 4 h	62.9	53.4	76	55	35	
Average			63.3	53.3	79	56	36	
Z250	L	500°F, 8 h	64.1	53.5	74	52	35	
Z218	L	500°F, 8 h	63.5	48.8	74	52	34	
Z219	L	500°F, 8 h	63.8	50.7	70	50	34	
Average			63.8	51.0	73	51	34	
Z230	T	500°F, 8 h	63.3	52.3	66	49	32	
Z231	T	500°F, 8 h	62.7	50.7	66	50	33	
Z232	T	500°F, 8 h	63.0	51.4	46	38	26	
Average			63.0	51.5	59	46	30	
Z220	L	600°F, 1 h	63.9	52.6	68	50	33	
Z221	L	600°F, 1 h	63.3	51.9	68	49	32	157
Z222	L	600°F, 1 h	62.8	50.8	68	48	32	
Average			63.3	51.8	68	49	32	157
Z233	T	600°F, 1 h	62.2	51.1	82	57	37	
Z235	T	600°F, 1 h	62.4	49.5	74	53	34	
Z236	T	600°F, 1 h	62.3	50.0	78	57	36	
Average			62.3	50.2	78	56	36	

TABLE V (cont)

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
Z223	L	600°F, 2 h	64.0	50.4	68	49	32	
Z224	L	600°F, 2 h	64.0	50.7	72	53	34	
Z225	L	600°F, 2 h	64.1	51.6	62	46	31	
Average			64.0	50.9	67	49	32	
Z237	T	600°F, 2 h	62.6	51.1	72	53	34	
Z238	T	600°F, 2 h	61.6	51.3	74	54	36	
Z239	T	600°F, 2 h	61.6	50.7	74	54	36	
Average			61.9	51.0	73	54	35	
Z226	L	600°F, 4 h	62.8	50.7	70	50	33	160
Z227	L	600°F, 4 h	62.8	52.1	68	49	32	
Z212	L	600°F, 4 h	62.3	49.7	64	48	32	
Average			62.6	50.8	67	49	32	160
Z213	T	600°F, 4 h	62.0	53.3	70	53	34	
Z214	T	600°F, 4 h	62.0	51.5	70	53	35	
Z215	T	600°F, 4 h	61.9	51.7	72	51	34	
Average			62.0	52.2	71	52	34	
Z229	L	600°F, 8 h	61.2	50.0	52	40	28	
Z256	L	600°F, 8 h	58.0	44.9	26	18	12	
Z257	L	600°F, 8 h	60.5	48.2	38	30	22	162
Average			59.9	47.7	39	29	21	162
Z216	T	600°F, 8 h	60.1	51.1	26	23	18	
Z251	T	600°F, 8 h	56.8	46.0	26	18	11	160
Z252	T	600°F, 8 h	57.6	42.2	20	14	10	
Average			58.2	46.4	24	18	13	160

^aZ100 series indicates the first sheet and Z200 series indicates the second sheet.

^bL = longitudinal and T = transverse to rolling direction.

^cBased on 0.2% offset from a 13.8×10^6 modulus line drawn tangent as near the origin as possible of a curve traced from signals from a 1-in. strain gauge, clip-on extensometer, and load values.

TABLE VI
TENSILE PROPERTIES OF HYDROGEN-EXPOSED Nb-1 WT% Zr ALLOY

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
N101	L	None	37.9	26.1	59	43	34	105
N128	L	None	37.7	26.4	61	47	35	
N140	L	None	37.6	26.8	52	39	31	
N141	L	None	37.1	27.4	63	43	35	
N142	L	None	37.5	25.4	66	45	36	
N143	L	None	37.3	25.9	70	47	36	
N201	L	None	37.8	25.4	64	51	38	
N228	L	None	37.6	27.5	63	48	36	
N240	L	None	37.2	26.7	67	51	38	
N241	L	None	35.9	24.9	60	44	36	
N242	L	None	36.4	25.0	66	50	38	
N243	L	None	37.3	25.3	67	50	38	
Average			37.3	26.1	63	47	36	
N102	T	None	37.8	25.4	62	45	34	90
N117	T	None	37.3	25.3	64	46	37	
N134	T	None	37.3	26.0	54	43	34	
N103	T	None	36.5	25.6	61	42	33	
N104	T	None	37.5	26.1	59	45	34	
N105	T	None	36.2	24.9	64	46	35	
N202	T	None	36.8	25.5	—	—	—	
N217	T	None	36.5	26.6	67	48	36	
N234	T	None	36.7	25.2	66	48	36	
N203	T	None	35.4	24.2	62	46	34	
N204	T	None	36.3	25.1	60	43	33	
N205	T	None	38.6	26.1	66	48	36	
Average			36.9	25.5	62	45	35	
N144	L	200°F, 1/2 h	38.8	26.9	68	49	37	90
N145	L	200°F, 1/2 h	37.4	24.9	66	49	37	
N146	L	200°F, 1/2 h	37.2	25.0	64	47	36	
Average			37.8	25.6	66	48	37	80
N106	T	200°F, 1/2 h	36.3	24.8	60	43	33	
N107	T	200°F, 1/2 h	37.5	25.9	59	43	33	
N108	T	200°F, 1/2 h	37.7	26.4	56	41	31	
Average			37.5	25.7	58	42	32	
N147	L	200°F, 1 h	37.7	25.5	60	44	34	80
N148	L	200°F, 1 h	37.6	25.6	70	48	36	
N149	L	200°F, 1 h	37.6	26.9	64	47	35	
Average			37.6	26.0	65	46	35	

TABLE VI (cont)

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
N109	T	200°F, 1 h	36.7	25.5	57	42	32	90
N110	T	200°F, 1 h	36.2	24.8	58	42	32	
N111	T	200°F, 1 h	37.1	25.4	57	44	34	
Average			36.7	25.2	57	43	33	
N150	L	200°F, 2 h	39.2	27.9	61	44	34	
N118	L	200°F, 2 h	38.6	26.6	65	48	36	
N119	L	200°F, 2 h	38.6	26.6	65	47	36	
Average			38.8	27.0	64	46	35	
N130	T	200°F, 2 h	37.7	26.7	62	45	34	
N131	T	200°F, 2 h	37.8	26.4	65	48	36	
N132	T	200°F, 2 h	37.7	26.7	60	46	35	
Average			37.7	26.6	62	46	35	
N120	L	400°F, 1/2 h	39.7	26.8	61	45	34	90
N121	L	400°F, 1/2 h	40.3	27.1	58	42	34	
N122	L	400°F, 1/2 h	40.6	27.0	52	42	34	
Average			39.6	27.0	57	43	34	
N133	T	400°F, 1/2 h	39.9	27.6	65	47	35	
N135	T	400°F, 1/2 h	41.5	28.7	61	45	33	
N136	T	400°F, 1/2 h	40.7	27.9	61	45	34	
Average			40.7	28.1	62	46	34	
N123	L	400°F, 1 h	39.7	24.0	56	43	33	
N124	L	400°F, 1 h	39.4	24.9	58	45	34	
N125	L	400°F, 1 h	38.6	24.5	58	44	33	
Average			39.2	24.5	57	44	33	
N137	T	400°F, 1 h	39.6	26.8	65	47	34	100
N138	T	400°F, 1 h	39.7	27.8	57	42	32	
N139	T	400°F, 1 h	39.5	26.8	71	50	36	
Average			39.6	27.1	64	46	34	
N126	L	400°F, 2 h	39.7	26.3	60	45	34	
N127	L	400°F, 2 h	39.8	26.1	64	46	35	
N112	L	400°F, 2 h	38.6	25.2	58	42	35	
Average			39.4	25.9	61	44	35	
N113	T	400°F, 2 h	39.2	26.6	60	44	33	
N114	T	400°F, 2 h	39.8	26.9	50	42	32	
N115	T	400°F, 2 h	38.8	25.6	70	50	38	
Average			39.3	26.4	60	45	34	
N244	L	600°F, 1/2 h	46.8	30.9	66	48	36	100
N245	L	600°F, 1/2 h	47.4	30.2	66	47	36	
N246	L	600°F, 1/2 h	47.6	32.1	59	46	35	
Average			47.3	31.1	64	47	36	

TABLE VI (cont)

Sample ^a	Orientation ^b	Hydrogen Treatment	Tensile Strength (kpsi)	Yield Strength ^c (kpsi)	Percent Elongation			Hardness (DPH)
					1/4 in.	1/2 in.	1 in.	
N206	T	600°F, 1/2 h	47.4	31.8	60	46	35	
N207	T	600°F, 1/2 h	46.6	30.7	69	49	36	
N208	T	600°F, 1/2 h	49.2	33.3	63	46	34	
Average			47.7	31.9	64	47	35	
N247	L	600°F, 1 h	44.6	37.6	6	3	2	120
N248	L	600°F, 1 h	45.3	38.2	4	2	2	
N249	L	600°F, 1 h	44.1	39.3	2	2	1	
Average			44.7	38.4	4	2	2	
N209	T	600°F, 1 h	46.1	37.2	4	3	3	120
N210	T	600°F, 1 h	44.5	37.7	4	3	2	
N211	T	600°F, 1 h	45.6	38.8	4	3	2	
Average			45.4	37.9	4	3	2	
N250	L	600°F, 2 h	44.7	38.7	4	2	2	115
N218	L	600°F, 2 h	47.3	37.7	6	6	4	
N219	L	600°F, 2 h	45.2	31.7	5	5	4	
Average			45.7	36.0	5	5	3	
N230	T	600°F, 2 h	41.1	38.0	4	2	1	
N231	T	600°F, 2 h	41.9	34.7	3	1	1	
N232	T	600°F, 2 h	43.6	37.8	4	3	2	
Average			42.2	36.8	4	2	1	

^aN100 series indicates the first sheet and N200 series indicates the second sheet.

^bL = longitudinal and T = transverse to rolling direction.

^cBased on 0.2% offset from a 15×10^6 modulus line drawn tangent as near the origin as possible of a curve traced from signals from a 1-in. strain gauge, clip-on extensometer, and load values.