TENSILE PROPERTIES OF UNIRRADIATED V-Cr-Ti ALLOYS, AND ALTERNATIVE APPROACHES FOR STRENGTHENING THE V-4Cr-4Ti ALLOY* - B. A. Loomis, L. J. Nowicki, and D. L. Smith (Argonne National Laboratory)

OBJECTIVE

The objective of this research is to determine the temperature dependence of physical and mechanical properties of unirradiated and neutron-irradiated V-Cr-Ti alloys for the purpose of determining the composition of a V-Cr-Ti alloy with the optimal combination of physical and mechanical properties in the environment of a magnetic fusion reactor.

SUMMARY

The temperature dependence of tensile properties of unirradiated V-Cr-Ti alloys are presented in the form of tables and figures in this report. These tensile-property data, together with other physical and mechanical property data for unirradiated and neutron-irradiated V-Cr-Ti alloys, are examined for alternative approaches to strengthen the V-4Cr-4Ti alloy, which is the current prime-candidate vanadium-base alloy for use as structural material in a fusion reactor. Consideration of three alternative approaches for strengthening (i.e., increased Cr and/or Ti concentration; heat treatment; or increased Si and/or Si, Al, and Y concentration) lead us to recommend Si and/or Si, Al, and Y additions as most promising for strengthening of the V-4Cr-4Ti alloy without major impact on the physical and mechanical properties of V-4Cr-4Ti.

MATERIALS AND PROCEDURES

Unalloyed vanadium and vanadium-base alloys with the compositions listed in Table 1 were obtained in the form of ≈50% cold-worked sheet with a thickness of ≈0.9 mm. Tensile specimens with a gauge length of 7.62 mm and a gauge width of 1.52 mm were machined from the as-received sheet. Surfaces of the tensile specimens were mechanically ground and polished to a surface finish of ≈0.3 μm. The polished tensile specimens were recrystallized by annealing for 1 h in a vacuum of 2×10^{-5} Pa. The unalloyed vanadium and V-1Ti alloy were annealed at 1050°C; the V-3Ti, V-3Ti-0.25Si, V-3Ti-0.5Si, V-3Ti-1Si, V-5Ti, V-10Ti, and V-18Ti alloys were annealed at 1100°C; and the V-5Cr-3Ti, V-4Cr-4Ti, V-5Cr-5Ti, V-8Cr-6Ti, V-9Cr-5Ti, V-11Cr-5Ti, V-13Cr-6Ti, V-14Cr-5Ti, V-15Cr-5Ti, V-10Cr-9Ti, V-7Cr-15Ti, and Vanstar-7 alloys were annealed at 1125°C. These annealing temperatures resulted in an average recrystallized grain diameter of 20-30 μm.

The tensile specimens were tested at a tensile strain rate of 0.0011 s^{-1} and a crosshead speed of 0.008 $mm \cdot s^{-1}$. The tensile tests were conducted in an environment of flowing argon ($3 \times 10^{-5} m^3 \cdot s^{-1}$) of 99.9999% purity. Specimen temperature was determined by a chromel-alumel thermocouple that was arc-welded to the edge of the specimen; the temperature of each specimen during the tensile test was controlled to ±1°C.

The compositions of V-4Cr-5Ti-1Si,Al,Y and V-14Cr-25Ti-1Si,Al,Y alloys investigated by Satou et al. [1] are also listed in Table 1. These tensile specimens were annealed for 1 h at 1100°C, which resulted in an average grain diameter of 20 μm.

EXPERIMENTAL RESULTS

The yield strength (YS), ultimate tensile strength (UTS), uniform elongation (E_U), and total elongation (E_T) for the unalloyed vanadium and vanadium alloys listed in Table 1 are presented in Table 2. Yield strength in Table 2 is defined at either the yield point or at 0.2% E_T from the elastic portion of the tensile load-elongation curve. The tensile properties data in Table 2 include those (with minor corrections) previously presented in Ref. 2.

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Table 1. Composition of Unalloyed Vanadium and Vanadium-base Alloys

Material	ANL ID	Cr, wt.%	Ti, wt.%	Al, Fe, Y, Zr wt.%	O, wt. ppm	N, wt. ppm	C, wt. ppm	Si, wt. ppm
V	BL 51	–	–	0.03 A1	297	35	30	287
V-lTi	BL 50	–	1.0	0.08 Al	230	130	235	1050
V-3Ti	BL 62	–	3.1	0.07 Al	320	86	109	660
V-3Ti-0.25Si	BL 27	–	3.1	0.04 Fe	210	310	300	2500
V-3Ti-0.5Si	BL 42		3.1	0.02 Fe	580	190	140	5400
V-3Ti-1Si	BL 45	–	2.5	0.01 Fe	345	125	90	9900
V-5Ti	BL 46	–	4.6	0.04 Al	305	53	85	160
V-l0Ti	BL 12	–	9.8	0.63 Fe	1670	390	450	245
V-18Ti	BL 15	–	17.7	0.04 Fe	830	160	380	480
V 5Cr-3Ti	BL 54	5.1	3.0	0.07 Al	480	82	133	655
V-4Cr-4Ti	BL 47	4.1	4.3	0.03 Al	350	220	200	870
V-5Cr-5Ti	BL 63	4.6	5.1	0.02 Al	440	28	73	310
V-8Cr-6Ti	BL 49	7.9	5.7	0.02 Al	400	150	127	36
V-9Cr-5Ti	BL 43	9.2	4.9	0.02 Fe	230	31	100	340
V-11Cr-5Ti	BL 40	10.9	5.0	0.04 Fe	470	80	90	270
V-13Cr-6Ti	BL 23	12.9	5.9	0.04 Fe	400	490	280	1230
V-14Cr-5Ti	BL 24	13.5	5.2	0.05 Fe	1190	360	500	390
V-15Cr-5Ti	BL 41	14.5	5.0	0.02 Fe	330	96	120	400
V-l0–Cr-9Ti	BL 44	9.9	9.2	0.04 Fe	300	87	150	270
V-7Cr-15Ti	BL 10	7.2	14.5	0.09 Fe	1110	250	400	400
V-4Cr-5Ti 1Si,Al,Y	–	4.0	4.8	0.95 Al 0.77 Y	126	140	54	8500
V-14Cr-25Ti-1Si,Al,Y	–	13.5	24.6	0.54 A1 0.71Y	250	75	187	9800
Vanstar-7	BL 28	9.7	–	3.50 Fe 1.30 Zr	280	520	640	–

Table 2. Tensile Properties of Vanadium and V-Cr-Ti Alloys*

Material	ANL ID	Test Temp., °C	YS, MPa	UTS, MPa	E_u, %	E_t, %
V	BL 51	25	259	309	28	49
V	"	100	220	290	24	32
V	"	225	175	279	21	28
V	"	300	181	348	26	32
V	"	325	153	335	24	32
V	"	350	138	310	24	32
V	"	420	167	283	25	36
V	"	520	134	187	34	65
V	"	600	124	134	28	64
V	"	700	124	124	28	64
V-3Ti	BL 62	25	295	409	24	33
V-3Ti	"	100	210	340	22	27
V-3Ti	"	225	180	298	22	28
V-3Ti	"	325	177	350	20	24
V-3Ti	"	420	183	404	20	26
V-3Ti	"	520	170	406	19	23
V-3Ti	"	600	177	410	21	25
V-3Ti	"	700	183	405	19	23
V-3Ti-0.5Si	BL 42	25	473	545	20	26
V-3Ti-0.5Si	"	100	405	519	19	22
V-3Ti-0.5Si	"	225	317	410	18	23
V-3Ti-0.5Si	"	325	300	436	21	27
V-3Ti-0.5Si	"	420	328	463	16	20
V-3Ti-0.5Si	"	520	312	466	18	23
V-3Ti-0.5Si	"	600	308	470	18	21
V-3Ti-0.5Si	"	700	291	452	17	20
V-5Ti	BL 46	25	336	412	22	35
V-5Ti	"	108	294	366	16	24
V-5Ti	"	160	259	342	20	25
V-5Ti	"	225	217	317	23	28
V-5Ti	"	330	214	342	22	28
V-5Ti	"	420	215	334	15	19
V-5Ti	"	520	195	350	20	24
V-5Ti	"	600	195	388	19	25
V-5Ti	"	700	203	376	17	19

Material	ANL ID	Test Temp., °C	YS, MPa	UTS, MPa	E_u, %	E_t, %
V-1Ti	BL 50	25	268	343	23	34
V-1Ti	"	120	236	317	23	34
V-1Ti	"	225	188	275	20	28
V-1Ti	"	325	174	396	23	29
V-1Ti	"	420	198	402	22	28
V-1Ti	"	520	181	398	28	37
V-1Ti	"	600	174	351	24	32
V-1Ti	"	700	157	317	21	29
V-3Ti-0.25Si	BL 27	25	367	465	24	33
V-3Ti-0.25Si	"	100	300	410	22	27
V-3Ti-0.25Si	"	225	235	344	22	28
V-3Ti-0.25Si	"	325	227	386	20	24
V-3Ti-0.25Si	"	420	242	431	20	26
V-3Ti-0.25Si	"	520	228	428	19	23
V-3Ti-0.25Si	"	600	230	435	21	25
V-3Ti-0.25Si	"	700	224	413	19	23
V-3Ti-1Si	BL 45	25	421	480	25	34
V-3Ti-1Si	"	105	355	430	26	33
V-3Ti-1Si	"	225	286	392	26	32
V-3Ti-1Si	"	325	259	405	21	26
V-3Ti-1Si	"	420	274	447	24	29
V-3Ti-1Si	"	520	274	447	24	29
V-3Ti-1Si	"	600	265	446	21	26
V-3Ti-1Si	"	700	260	437	17	21
V-10Ti	BL 12	25	435	532	25	33
V-10Ti	"	100	374	477	25	32
V-10Ti	"	225	326	463	23	28
V-10Ti	"	325	310	479	21	27
V-10Ti	"	420	308	496	21	27
V-10Ti	"	520	303	529	21	25
V-10Ti	"	600	298	538	23	25
V-10Ti	"	700	262	466	19	24

Table 2. (Continued)

Material	ANL ID	Test Temp., °C	YS, MPa	UTS, MPa	E_u, %	E_t, %
V-18Ti	BL 15	25	628	692	22	32
V-18Ti	"	100	525	640	22	30
V-18Ti	"	225	437	588	20	25
V-18Ti	"	325	436	636	24	29
V-18Ti	"	420	443	658	24	30
V-18Ti	"	520	445	678	29	33
V-18Ti	"	600	417	667	20	28
V-18Ti	"	700	393	496	15	23
V-5Cr-5Ti	BL 63	25	386	465	22	34
V-5Cr-5Ti	"	420	238	396	21	28
V-5Cr-5Ti	"	600	225	382	15	20
V-4Cr-5Ti-1Si,Al,Y	–	25	510	57	–	20
"	"	200	425	510	–	20
"	"	300	375	500	–	21
"	"	400	350	525	–	19
"	"	500	345	525	–	19
"	"	600	345	550	–	19
"	"	700	300	475	–	22
"	"	800	275	400	–	40
"	"	900	250	285	–	60
"	"	1000	150	175	–	70
V-9Cr-5Ti	BL 43	25	440	541	23	33
V-9Cr-5Ti	"	100	387	482	20	32
V-9Cr-5Ti	"	225	334	448	22	29
V-9Cr-5Ti	"	325	312	452	21	30
V-9Cr-5Ti	"	420	300	467	20	25
V-9Cr-5Ti	"	520	297	463	18	23
V-9Cr-5Ti	"	600	297	512	21	25
V-9Cr-5Ti	"	700	277	488	21	27
V-5Cr-3Ti	BL 54	25	337	430	18	25
V-5Cr-3Ti	"	420	208	349	17	23
V-5Cr-3Ti	"	600	204	346	14	21
V-4Cr-4Ti	BL 47	25	387	454	25	34
V-4Cr-4Ti	"	100	325	420	25	33
V-4Cr-4Ti	"	225	272	379	26	31
V-4Cr-4Ti	"	337	254	388	20	28
V-4Cr-4Ti	"	420	250	405	21	25
V-4Cr-4Ti	"	520	244	423	19	24
V-4Cr-4Ti	"	600	256	434	16	21
V-4Cr-4Ti	"	650	264	453	19	23
V-4Cr-4Ti	"	700	266	414	17	20
V-8Cr-6Ti	BL 49	25	440	541	23	33
V-8Cr-6Ti	"	108	393	489	23	30
V-8Cr-6Ti	"	175	318	404	12	13
V-8Cr-6Ti	"	225	236	347	17	23
V-8Cr-6Ti	"	325	261	429	18	26
V-8Cr-6Ti	"	420	287	470	20	25
V-8Cr-6Ti	"	600	285	486	19	22
V-8Cr-6Ti	"	700	271	487	21	26
V-11Cr-5Ti	BL 40	25	491	573	23	31
V-11Cr-5Ti	"	100	402	500	21	27
V-11Cr-5Ti	"	225	347	464	21	26
V-11Cr-5Ti	"	325	304	448	17	24
V-11Cr-5Ti	"	433	321	501	18	24
V-11Cr-5Ti	"	520	303	488	17	22
V-11Cr-5Ti	"	600	299	519	22	26
V-11Cr-5Ti	"	650	310	529	20	25
V-11Cr-5Ti	"	700	299	513	21	26

Table 2. (Continued)

Material	ANL ID	Test Temp., °C	YS, MPa	UTS, MPa	E_u, %	E_t, %	Material	ANL ID	Test Temp., °C	YS, MPa	UTS, MPa	E_u, %	E_t, %
V-13Cr-6Ti	BL 23	25	533	627	25	37	V-14Cr-5Ti	BL 24	25	545	634	23	32
V-13Cr-6Ti	"	100	483	589	25	37	V-14Cr-5Ti	"	100	439	545	22	31
V-13Cr-6Ti	"	225	407	548	23	29	V-14Cr-5Ti	"	225	370	478	17	25
V-13Cr-6Ti	"	325	368	522	23	30	V-14Cr-5Ti	"	325	317	449	17	23
V-13Cr-6Ti	"	420	379	571	21	27	V-14Cr-5Ti	"	420	341	518	21	27
V-13Cr-6Ti	"	520	360	567	21	27	V-14Cr-5Ti	"	520	326	502	17	23
V-13Cr-6Ti	"	600	384	610	25	31	V-14Cr-5Ti	"	600	342	555	21	26
V-13Cr-6Ti	"	650	373	573	22	30	V-14Cr-5Ti	"	650	342	559	25	30
V-13Cr-6Ti	"	700	355	519	21	32	V-14Cr-5Ti	"	700	337	544	21	26
V-15Cr-5Ti	BL 41	25	570	674	26	33	V-l0Cr-9Ti	BL 44	25	534	628	24	34
V-15Cr-5Ti	"	100	494	579	23	29	V-l0Cr-9Ti	"	100	469	571	24	36
V-15Cr-5Ti	"	225	399	525	22	27	V-l0Cr-9Ti	"	225	387	516	21	29
V-15Cr-5Ti	"	325	348	500	19	26	V-l0Cr-9Ti	"	325	367	532	23	30
V-15Cr-5Ti	"	420	346	524	20	26	V-l0Cr-9Ti	"	420	364	570	23	30
V-15Cr-5Ti	"	520	350	538	19	25	V-l0Cr-9Ti	"	520	349	560	23	29
V-15Cr-5Ti	"	600	335	560	21	25	V-l0Cr-9Ti	"	600	352	565	23	30
V-15Cr-5Ti	"	700	339	564	22	28	V-l0Cr-9Ti	"	700	328	492	20	28
V-7Cr-15Ti	BL 10	25	636	717	20	28	V-14Cr-25Ti-1Si,Al,Y	–	25	960	1025	–	8
V-7Cr-15Ti	"	100	556	647	21	28	"	"	200	815	940	–	15
V-7Cr-15Ti	"	225	490	618	20	25	"	"	300	875	1000	–	17
V-7Cr-15Ti	"	325	487	682	21	25	"	"	400	760	975	–	18
V-7Cr-15Ti	"	420	471	695	22	29	"	"	500	725	985	–	15
V-7Cr-15Ti	"	520	468	730	24	28	"	"	600	720	1025	–	20
V-7Cr-15Ti	"	600	469	738	26	27	"	"	700	590	800	–	19
V-7Cr-15Ti	"	700	404	584	18	30	"	"	800	525	625	–	35
							"	"	1000	150	175	–	70
Vanstar-7	BL 28	25	411	571	25	37	Vanstar-7	BL 28	425	240	467	27	33
Vanstar-7	"	105	337	501	28	35	Vanstar-7	"	520	239	450	27	33
Vanstar-7	"	225	279	462	24	31	Vanstar-7	"	600	251	413	26	34
Vanstar-7	"	325	249	455	23	29	Vanstar-7	"	700	219	355	26	35

*Data for the V–4Cr–5Ti–1Si, Al, Y and V–14Cr–25Ti–1Si, Al, Y alloys were obtained from Ref. 1.

Dependence of yield strength of V-Ti and V-Cr-(4-6)Ti alloys at 25°C on Cr + Ti concentration is shown in Fig. 1, which shows that the yield strength of V-Ti and V-Cr-Ti alloys is strongly dependent on Ti and/or Cr concentration, with Ti a more potent strengthener than Cr. As shown in Figs. 2 and 3, Si can also be a potent strengthener of V-Ti and V-Cr-Ti alloys. Maximum strengthening of these alloys by Si may be 5000 to 10000 ppm Si (Fig. 2).

Additional figures (constructed from the data in Table 2) that show the temperature dependence of yield strength, ultimate tensile strength, uniform elongation, and total elongation of V-Ti and V-Cr-Ti alloys are provided in Refs. 2 and 3.

DISCUSSION OF RESULTS

Extensive investigations on the effects of neutron irradiation on swelling, tensile properties, impact toughness, and microstructural evolution of V-Ti and V-Cr-Ti alloys on neutron irradiation have shown that the V-4Cr-4Ti alloy can be expected to have acceptable physical and mechanical properties in the harsh environment of a fusion reactor [4-6]. Nevertheless, it may be desirable to increase the strength of this alloy for additional resistance to thermal- and irradiation-induced creep and fatigue deformation [7-9]. At least three approaches might be used to strengthen the V-4Cr-4Ti alloy, i.e., (a) increased Cr and/or Ti concentration, (b) heat treatment, or (c) increased Si and/or Si, Al, and Y concentration.

Increased Cr and/or Ti Concentration

The strength of V-Ti and V-Cr-Ti alloys is strongly dependent on Cr and/or Ti concentration in the alloy, as shown in Fig. 1. However, if Cr or Ti concentration in the alloy is increased to >6%, the ductile-brittle transition temperature (DBTT) may be >25°C on neutron irradiation [5].

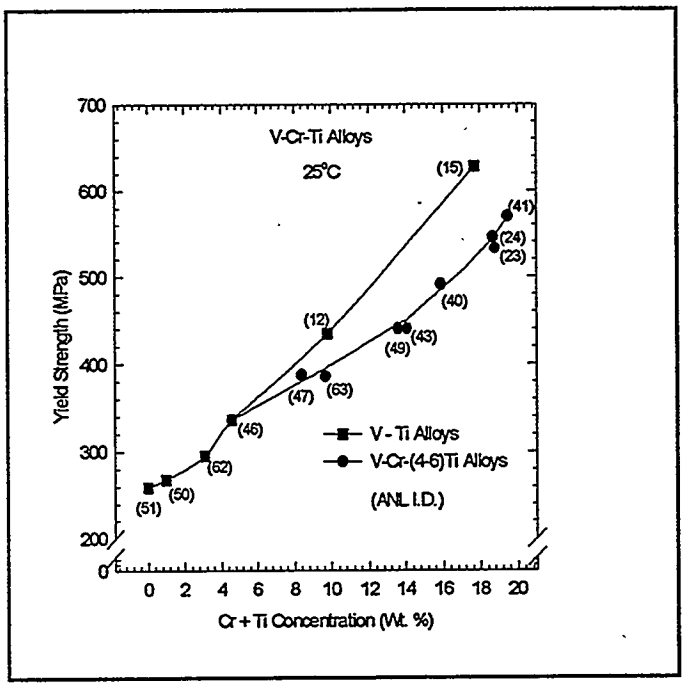

Fig. 1. Dependence of Yield Strength of V-Ti and V-Cr-(4-6)Ti Alloys at 25°C on Cr + Ti Concentration.

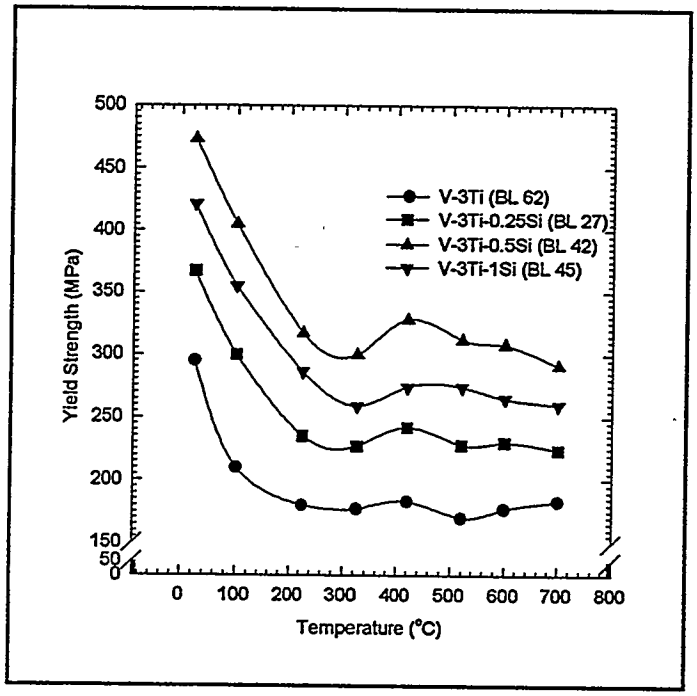

Fig. 2. Dependence of Yield Strength of V-3Ti-Si Alloys on Temperature.

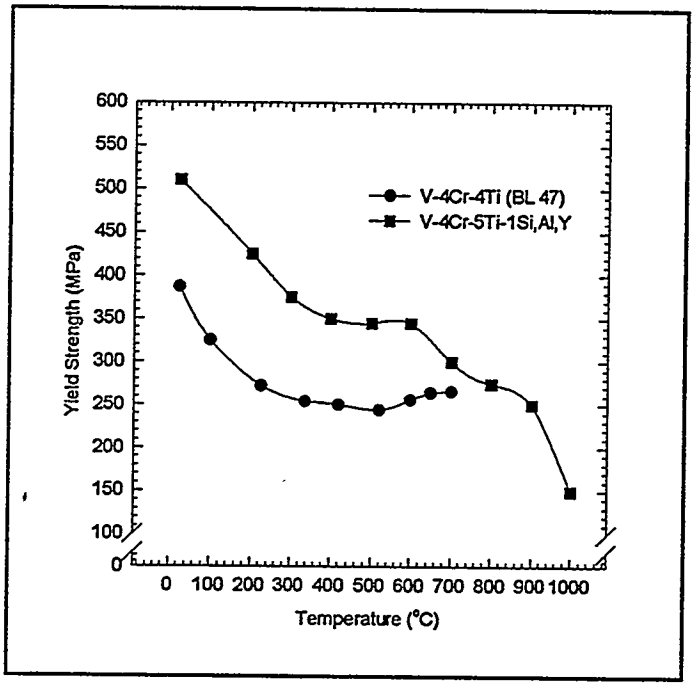

Fig. 3. Dependence of Yield Strength of V-4Cr-4Ti and V-4Cr-5Ti-1Si,Al,Y Alloys on Temperature.

Heat Treatment

The strength of V-Cr-Ti alloys is also strongly dependent on heat treatment as suggested by the data in Fig. 3 of Ref. 10. However, experimental data, e.g., Fig. 1 in Ref. 11, suggest that the swelling of V-Cr-Ti alloys may be increased significantly by reducing heat treatment temperature to <1100-1125°C.

Increased Si and/or Si, Al, and Y Concentration

The strength of the V-3Ti alloy and the V-4Cr-4Ti alloy is also strongly dependent on Si concentration in the alloy (Figs. 2 and 3). The addition of 9900 ppm Si to the V-3Ti alloy did not result in a significant increase in DBTT [5]. Total elongation of the V-4Cr-5Ti-1Si,Al,Y alloy at 25°C after irradiation at 420-600°C to 24-41 dpa was 8-15%, and swelling of this alloy after irradiation was low [12]. Therefore, the addition of Si (and possibly Al and Y) to the V-4Cr-4Ti alloy may be the most viable approach for strengthening of this alloy.

CONCLUSIONS

- The strength of V-Ti and V-Cr-Ti alloys is strongly dependent on Cr, Ti, and Si concentration.
- The addition of Si (and possibly Al and Y) to the V-4Cr-4Ti alloy may be the most viable approach for strengthening of this alloy.

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