EFFECT OF Cr AND Ti CONTENTS ON THE RECOVERY, RECRYSTALLIZATION, AND MECHANICAL PROPERTIES OF VANADIUM ALLOYS — A. N. Gubbi,

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OBJECTIVE

The aim of this work is to examine the effect of varying Cr and Ti contents on the recovery and recrystallization, and mechanical properties like yield stress, tensile strength and impact properties of small heats of vanadium alloys.

SUMMARY

A series of vacuum-anneals at temperatures from 900° to 100°C for 1 to 4 h was carried out on small heats of vanadium alloys with Cr and Ti contents ranging from 3 to 6 wt.%. The alloys examined in this work were V-3Cr-3Ti, V-4Cr-4Ti-Si, V-5Cr-5Ti, V-6Cr-3Ti and V-6Cr-6Ti. Optical microscopy, TEM and microhardness testing were conducted. Variation in Cr and Ti over the range 3 to 6 wt.% had no discernible effect on recovery/recrystallization behavior. The hardness of both recovered and recrystallized structures increased with total (Cr + Ti) content. In order to study the effect of Cr and Ti content on mechanical properties, Charpy impact testing and tensile testing were carried out on small heats of compositional variants. The V-4Cr-4Ti-Si alloy, in a fully recrystallized condition, exhibited a high level of resistance to cleavage failure with a DBTT at ~—190°C. The alloys containing higher concentrations of Cr and Ti, in a fully recrystallized condition, exhibited a DBTT at around —100°C, whereas the V-3Cr-3Ti alloy failed by pure ductile shear at liquid nitrogen temperature without any ductile-to-brittle transition. Tensile testing was conducted on SS-3 tensile specimens punched from 0.762-mm-thick plates of V-3Cr-3Ti and V-6Cr-6Ti. The tests were done in air at room temperature at strain rates ranging from 10^{-3} to 2×10^{-1}/s. For V-6Cr-6Ti, both the 0.2% yield stress (YS) and the ultimate tensile strength (UTS) were higher than those for V-3Cr-3Ti at all strain rates. Both YS and UTS showed a similar trend of incremental increase with strain rate for the two alloys. In the same token, both alloys exhibited an identical behavior of almost no change in uniform and total elongation up to a strain rate of 10^{-1}/s and a decrease with further increase in strain rate.

INTRODUCTION

In the early stages of the program on the development of alloys for fusion reactor applications, vanadium alloys with 3 to 6 wt.% Cr and Ti were investigated.[1-4] This composition range was subsequently narrowed down to vanadium alloys with 4 wt.% each of Cr and Ti based on the thermal creep properties, low DBTT under Charpy impact testing, resistance to swelling, and also resistance to helium- and irradiation-induced embrittlement exhibited by a laboratory-scale heat of this alloy.[5] A production-scale heat (~500-kg, heat 832665) of V-4Cr-4Ti alloy has been fabricated by Teledyne Wah Chang, Albany, Oregon (TWCA) recently. Impact data have been reported from the testing conducted on the samples machined from a warm-worked plate[6] as well as from an annealed plate.[7] Also, recovery and recrystallization behavior of this heat has been documented.[8] The present study reports the results from recovery and recrystallization study, and impact and tensile testing of the small heats of compositional variants with Ti and Cr contents ranging from 3 to 6 wt.%. These alloys will give the window for permissible ranges of Cr and Ti concentrations for consistent properties.

EXPERIMENTAL PROCEDURE

A small heat of (~15-kg melt) V-5Cr-5Ti (heat T87) was produced by Teledyne Wah Chang as per the specifications supplied by Argonne National Laboratory. Four small heats (each ~15-kg melt), V-3Cr-3Ti (heat T91), V-4Cr-4Ti-Si (heat T89), V-6Cr-3Ti (heat T92), and V-6Cr-6Ti (heat T90) were fabricated according to the specifications set by Oak Ridge National Laboratory. The samples for the recovery and recrystallization study were obtained from the rolled plates (~1.02-mm thick) of small heats. The

V-5Cr-5Ti alloy had a cold work level of approximately 40%[10] whereas the other small heats had a cold work of approximately 49%. The chemical compositions of the small heats of compositional variants have been presented elsewhere.[8]. Heat treatments were carried out on samples (for both optical metallography and TEM analysis) from 900° to 1100°C for 1 to 4 h in a vacuum better than 1×10^{-6} torr ($<10^{-4}$ Pa). Optical metallography, microhardness testing, and TEM analysis were carried out to understand the effect of temperature-time on the recovery and recrystallization of vanadium alloys.

One-third-size blunt-notch Charpy specimens (3.33 x 3.33 x 25.4 mm), with a notch that was 0.51 mm deep, with a root radius of 0.08 mm and an included angle of 30°, were obtained by electrodischarge machining from 3.81-mm-thick plates which were in a 40% warm-rolled (400°C) condition. All the specimens were oriented such that the crack could propagate parallel to the rolling direction. The machined Charpy samples were annealed at temperatures from 950° to 1050°C for 2 h in a vacuum better than 1×10^{-6} torr ($<10^{-4}$ Pa). Impact testing was carried out in a semiautomated pendulum-type impact testing system modified for subsize specimens.[9] Test temperatures employed were from –196° to 100°C with low temperatures being achieved by using liquid nitrogen. The results from the testing were fitted with a hyperbolic tangent function for determining the DBTT and upper-shelf energy. The lower-shelf energy was fixed at 0.2 J. The midpoint between the upper- and lower-shelf energy levels was considered as the DBTT. Fractography was done using a scanning electron microscope on the fracture surfaces obtained after the impact testing.

Tensile specimens (SS-3s) with a gauge length of 7.62 mm and a gauge width of 1.52 mm were punched from the as-received sheets. The punched samples were recrystallized by annealing for 2 h at 1000°C in a vacuum better than 1×10^{-6} torr ($<10^{-4}$ Pa). Tensile testing was carried out in air at room temperature at strain rates ranging from 1.1×10^{-3} to 2.2×10^{-1}/s.

RESULTS AND DISCUSSION

RECOVERY AND RECRYSTALLIZATION

The complete results from the recovery and recrystallization study on the compositional variants have been presented earlier.[8] No significant difference in recovery and recrystallization kinetics was observed among the five alloys examined. A major drop in hardness due to recovery by annihilation of dislocations and cell formation leading to nucleation of some new grains was observed for 900°C anneals. At 950°C, recrystallization proceeds from 20-30% after 1 h to 70-80% complete after 2 h. The recrystallization was almost fully complete for 1000°C anneals after 1-2 h. The grain growth was observed in all five alloys for anneals at 1050°C.

Figure 1 shows a plot of microhardness as a function of (Cr + Ti) content for alloys in a recovered (900°C) condition and in a fully recrystallized (1050°C) condition. The increasing dependence of hardness of V alloys on Cr and Ti concentration has been reported by Loomis et al.[11] and the data reported here follow the same trend. In the present data, however, there does seem to be a significant incremental step in hardness values when the combined Cr + Ti concentration exceeds ~9 wt.%. The 3Cr-3Ti, 4Cr-4Ti, and 6Cr-3Ti alloys have a minimum hardness in the range 130 to 142 DPH, whereas minimum hardness for the 5Cr-5Ti and 6Cr-6Ti alloys falls in the range 160 to 165 DPH.

IMPACT TESTING

A full report on the impact testing and fracture behavior of the compositional variants has been published earlier.[7] The 6Cr-3Ti alloy was tested with the following microstructures: recovered structure with small amount of recrystallization (after 2-h anneal at 950°C), a partially recrystallized structure (after 2-h anneal at 1000°C), and a fully recrystallized structure (after 2-h anneal at 1050°C). All the three microstructures showed a typical ductile-to-brittle transition behavior with a decrease in impact test temperature. The DBTT ranged from around –175°C for the recovered structure to around –75°C for the fully recrystallized structure which indicates that the final microstructure has a significant influence on the impact behavior.

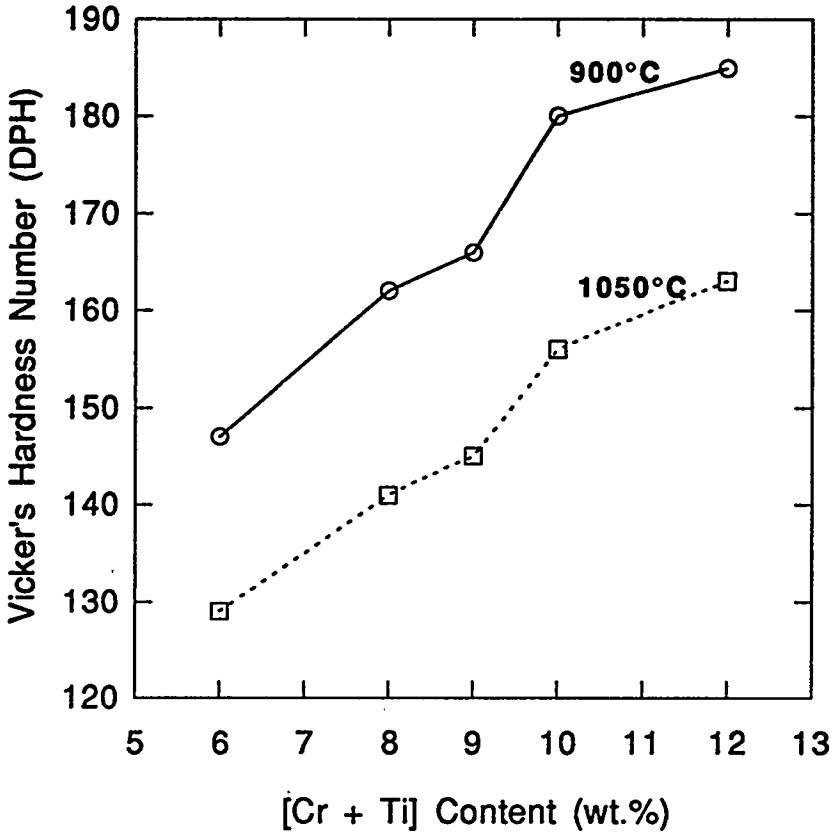

Figure 1. Variation of Hardness with (Cr + Ti) content
(All 2-h anneals)

Figure 2 shows the results from the Charpy impact testing with absorbed energy as a function of test temperature for V-5Cr-5Ti (heat T87), V-3Cr-3Ti (heat T91), V-4Cr-4Ti-Si (heat T89), V-6Cr-3Ti (heat T92), and V-6Cr-6Ti (heat T90). All the alloys were annealed at 1000°C for 2 h to produce an almost fully recrystallized microstructure. The impact results shown in Fig. 2 can be placed into two groups: one group containing alloys with lower (Cr + Ti) contents, i.e. V-3Cr-3Ti and V-4Cr-4Ti-Si, and the other group having alloys with higher (Cr + Ti) contents, i.e. V-5Cr-5Ti, V-6Cr-3Ti, and V-6Cr-6Ti. The lower (Cr + Ti)-containing alloys exhibit excellent impact behavior with V-4Cr-4Ti-Si showing DBTT of around –175°C. The V-3Cr-3Ti alloy did not show any ductile-to-brittle transition and remained quite ductile even at –196°C with shelf energy around 12 J. The higher (Cr + Ti)-containing alloys, V-5Cr-5Ti, V-6Cr-3Ti, and V-6Cr-6Ti all had a DBTT of ~ –120°C. The only difference among these alloys is in the upper shelf energy with that for V-6Cr-3Ti being around 15 J and V-5Cr-5Ti and V-6Cr-6Ti having around 11 J. In a companion article,[8] it was reported that the microhardness of the same alloys studied in the present work was grouped in a similar fashion. In the fully recrystallized conditions, the lower (Cr + Ti)-containing alloys had lower microhardness values (130-140 DPH) compared to the higher (Cr + Ti)-containing alloys which possessed higher hardness values (155-160 DPH). Thus, the results of the impact testing in conjunction with the results from recovery and recrystallization study[8] indicate that there is an incremental change in the physical and mechanical properties when the combined (Cr + Ti) content exceeds ~8 wt %.

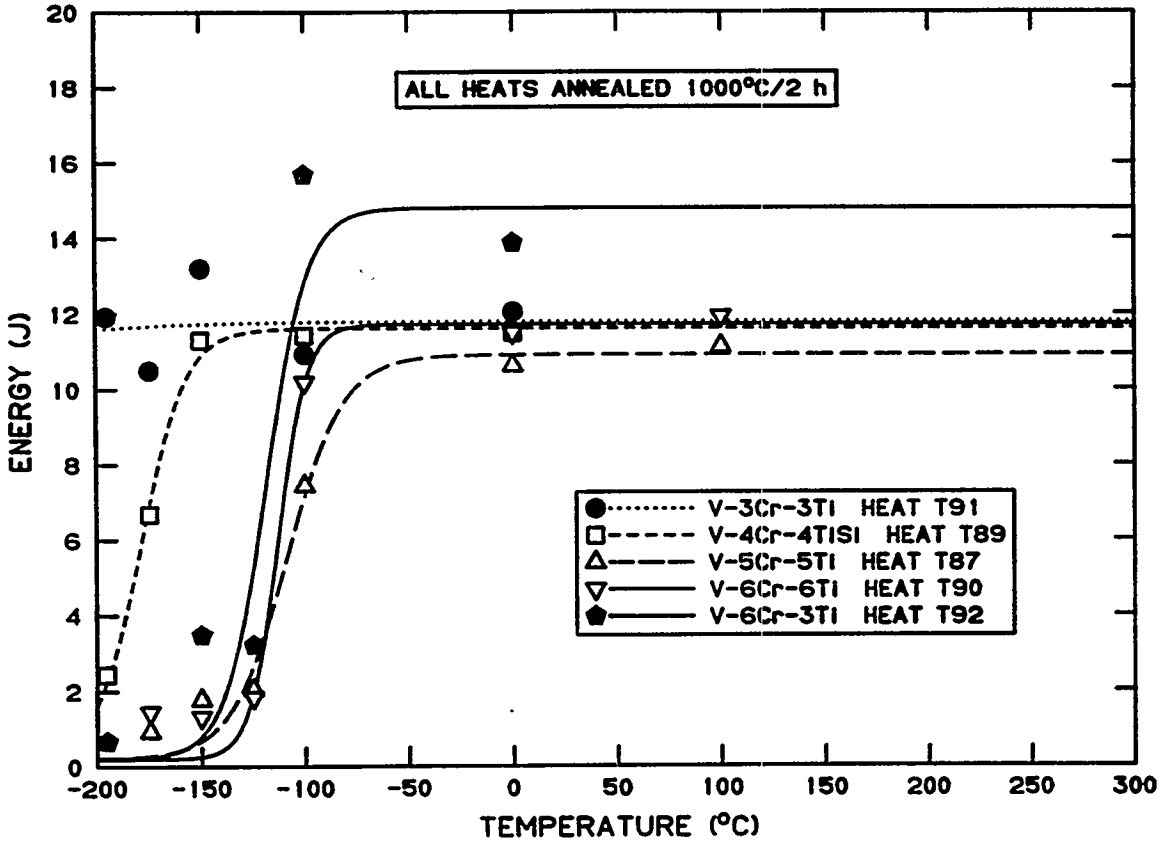

Figure 2. Third-size Charpy impact data for the Compositional Variants.

TENSILE TESTING

Figure 3 shows the variation of 0.2% yield stress (YS) with strain rate and Figure 4 shows the variation of ultimate tensile strength (UTS) with strain rate for the 3Cr-3Ti and 6Cr-6Ti alloys. Both alloys exhibited a general trend of incremental increase in YS and UTS with strain rate which is in line with the observed results for many metals. There is a marked difference in the YS and UTS of 3Cr-3Ti with those of 6Cr-6Ti for all strain rates tested. The V-6Cr-6Ti alloy was much stronger both at 0.2% strain and in UTS compared to the V-3Cr-3Ti alloy. It is useful to recall here the results of the microhardness testing from an earlier study[8] which showed that in both the recovered and fully recrystallized states, 6Cr-6Ti was much harder (160-185 DPH) than 3Cr-3Ti (130-140 DPH), see Fig. 1. Hence, the results of tensile testing in the present study in conjunction with the previous microhardness results reveal that the V-6Cr-6Ti alloy is an intrinsically stronger alloy (possibly due mainly to solid solution strengthening from higher Cr and Ti contents) compared to the V-3Cr-3Ti alloy. This strength difference may help explain the difference in the impact behavior (strain rate of ~10^3/s) observed in the previous study[7] between the V-6Cr-6Ti and V-3Cr-3Ti alloys. The V-3Cr-3Ti alloy did not show any ductile-to-brittle transition behavior whereas the V-6Cr-6Ti alloy showed a higher DBTT (compared to lower [Cr + Ti]-containing alloys) of around –120°C with both alloys exhibiting identical upper shelf energy of around 12 J, see Fig. 2.

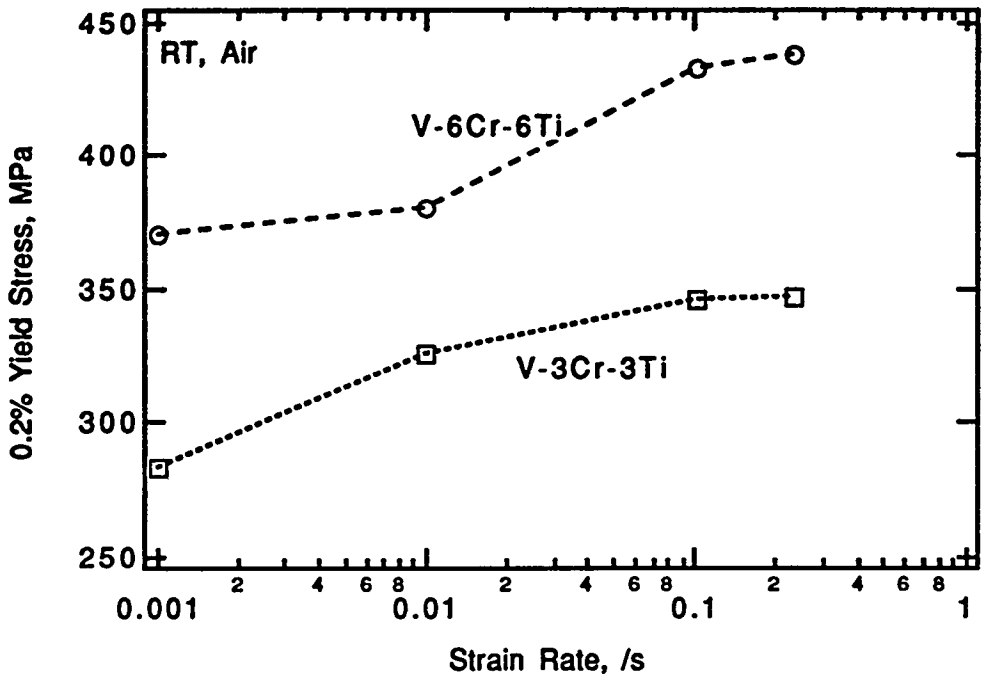

Figure 3. Variation of Yield Stress with Strain Rate for V-3Cr-3Ti and V-6Cr-6Ti.

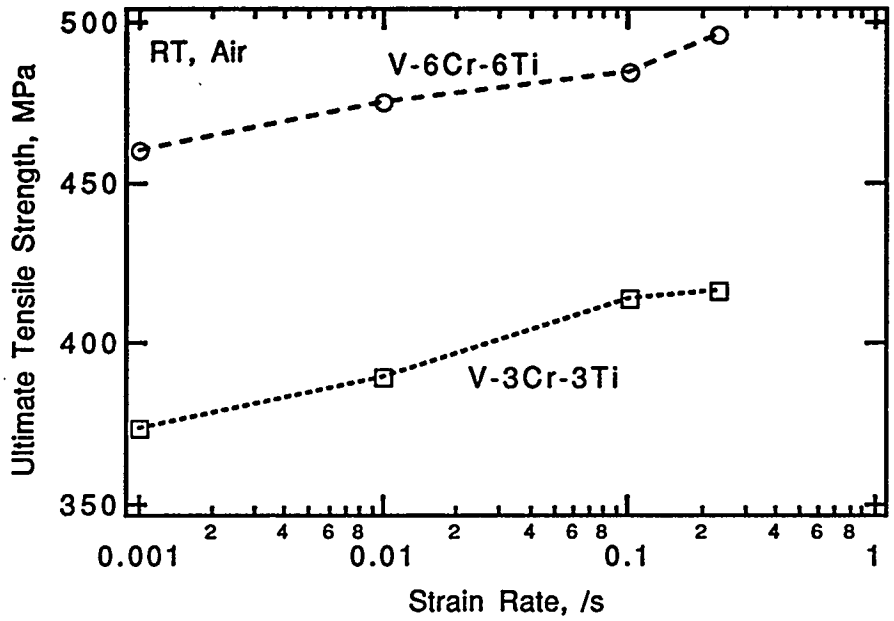

Figure 4. Variation of UTS with Strain Rate for V-3Cr-3Ti and V-6Cr-6Ti.

Figure 5 shows the variation of uniform elongation with strain rate for the 3Cr-3Ti and 6Cr-6Ti alloys. Both showed identical behavior with ductility exhibiting no change for strain rates up to 1×10^{-1}/s and a decrease for higher strain rate.

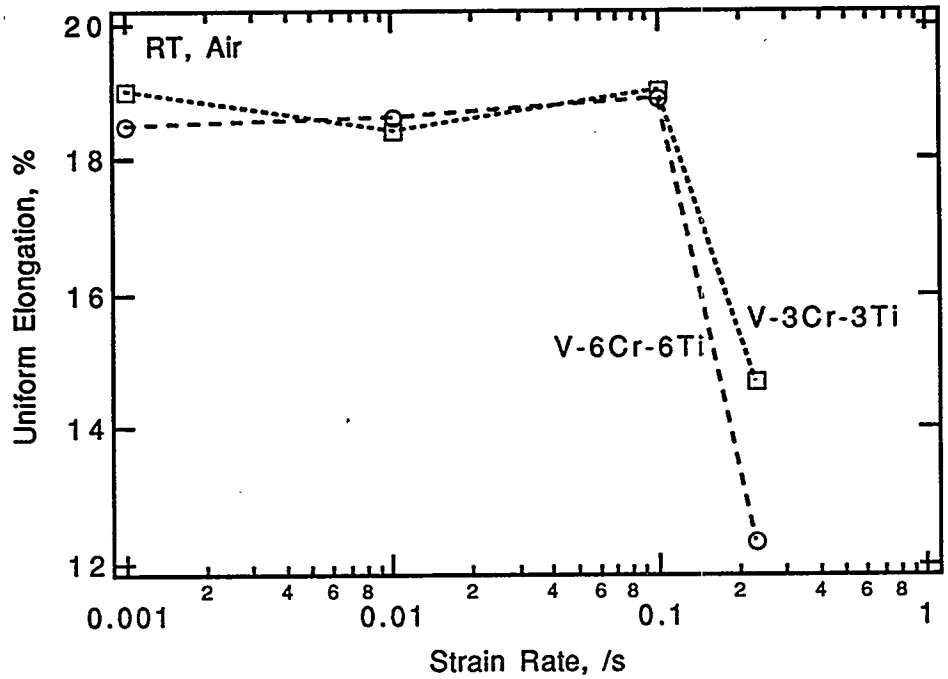

Figure 5. Uniform Elongation as a function of Strain Rate for V-3Cr-3Ti and V-6Cr-6Ti.

CONCLUSIONS

(1) Variations in Cr and Ti over the range 3 to 6 wt.% have no discernible effects on recovery and recrystallization kinetics; the hardness of both recovered and recrystallized structures increases with total (Cr + Ti) content.

(2) In a fully recrystallized microstructural condition, the Charpy impact properties of the compositional variants fall into two groups. Alloys containing a combined (Cr + Ti) content in excess of ~8 wt.% exhibit a DBTT of —120°C. Alloy containing 3Cr3Ti and 4Cr4Ti showed better resistance to cleavage fracture at low temperatures.

(3) The 0.2% yield stress and UTS, in general, increase with increase in strain rate for both 3Cr-3Ti and 6Cr-6Ti alloys. The V-6Cr-6Ti alloy was much stronger both at 0.2% strain and in UTS compared to the V-3Cr-3Ti alloy. The results of tensile testing in the present study in conjunction with the previous microhardness results reveal that the V-6Cr-6Ti alloy is an intrinsically stronger alloy (possibly due mainly to solid solution strengthening from higher Cr and Ti contents) compared to the V-3Cr-3Ti alloy.

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