FABRICATION AND IMPACT PROPERTIES OF LABORATORY-SCALE HEAT OF V–5Cr–5Ti*

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OBJECTIVE

The immediate objective of this work is to fabricate a new laboratory-scale heat of V–5Cr–5Ti and identify an optimal annealing procedure that produces the highest impact toughness in the alloy. By comparing the result with the optimal annealing procedure identified for production- and laboratory-scale heats of V–4Cr–4Ti, the long-range objective of the study is to demonstrate that excellent and reliable mechanical properties of the V–(4–5)Cr–(4–5)Ti alloy class can be produced by common fabrication and annealing procedures.

SUMMARY

Impact properties were determined on a new 15-kg laboratory heat of V-5Cr-5Ti, fabricated by the same procedures as those used to produce a 500-kg production-scale heat of V–4Cr–4Ti, to identify an optimal annealing procedure for the alloy. Charpy-impact tests were conducted on one-third-size specimens because low-temperature (<0°C) impact properties have been known to be most sensitive to the structure and toughness of the V–(4–5)Cr–(4–5)Ti alloy class. After final annealing at ≈1000°C for 1 h in a high-quality vacuum, the laboratory heat of V–5Cr–5Ti exhibited impact properties as excellent as those of the production- and laboratory-scale heats of V–4Cr–4Ti; i.e., ductile-brittle-transition temperatures less than –200°C and absorbed energies of 10–16 J. This finding demonstrates that, when fabricated by the procedure specified in this study and annealed at the common optimal condition of 1000°C for 1 h, the V–(4–5)Cr–(4–5)Ti alloy class exhibits excellent impact toughness and a sufficient tolerance to minor variations in alloying-element composition.

INTRODUCTION

V–(4–5)Cr–(4–5)Ti has been identified previously as the most promising vanadium-base candidate alloy for application in fusion reactor structural components.[1,2] Subsequently, some laboratory heats of V–5Cr–3Ti (ANL ID Heat BL–54) and V–5Cr–5Ti (BL–63), fabricated by procedures different from those that produced the excellent laboratory heat of V–4Cr–4Ti (ANL ID Heat BL–47), were found to exhibit impact properties significantly inferior to those of the V–4Cr–4Ti heat, in spite of small differences in alloying-element composition.[3] Because of this, two contrasting but related concerns were raised. One concern was on the tolerance of the most promising alloy V–4Cr–4Ti to inevitable minor variations in Cr and Ti content. The other was the reliability of fabrication, i.e., the effects of minor impurities, use of low-quality raw materials, and incorrect rolling and annealing procedures that may upset reliable fabrication of the alloy class.[3] Subsequently, a new 500-kg heat of V–4Cr–4Ti was produced successfully by a procedure essentially the same as that used to produce the excellent laboratory heat of V–4Cr–4Ti (Heat BL–47).[4] Charpy-impact testing showed that the new production-scale heat of V–4Cr–4Ti (Heat #832665) exhibited properties as excellent as those of the laboratory-scale heat of the alloy (i.e., BL–47).[5] Parallel to this effort, it was decided to fabricate a new laboratory-scale heat of V–5Cr–5Ti, hoping to demonstrate that the heat exhibits mechanical properties as good as those of V–4Cr–4Ti. This paper briefly outlines the fabrication procedure for a new 15-kg heat of V–5Cr–5Ti and presents comprehensive results of impact performance of the heat. By comparing the results with the optimal annealing procedure identified for V–4Cr–4Ti in a separate investigation,[5] the real objective of the study was to demonstrate that excellent and reliable mechanical properties of V–(4–5)Cr–(4–5)Ti alloy class can be produced by common fabrication and annealing procedures.

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EXPERIMENTAL PROCEDURES

The fabrication procedure for the 15–kg heat of V–5Cr–5Ti was essentially the same as that used for the 500–kg production–scale heat of V–4Cr–4Ti,[4] except that the former was produced in the laboratory, on a small scale; the latter was produced in the production facility of Teledyne Wah Chang in Albany, Oregon. Therefore, for details of specification and fabrication procedure, the reader is referred to Ref. 4. The same raw materials were used to melt the ingots of both heats by multiple vacuum–arc melting. Secondary fabrication procedures, i.e., extruding the ingot at 1150°C, subsequent cross–rolling (at 400°C), and heat treating between rolling (at 1050°C–1070°C) to manufacture final products in the form of plates and sheets of various thickness, were also similar.

The elemental composition of the alloy ingot and of the raw vanadium that was used to melt the alloy ingot, are given in Table 1. The raw vanadium feedstock was produced by electron–beam melting. Charpy–impact specimens, machined from the 3.8–mm–thick alloy plates, were cleaned, and annealed at high temperatures before testing. Typical test specimens were annealed at 1000, 1050, or 1100°C for 1 h in a high–quality ion–pumped vacuum system. Orientation of Charpy–impact specimens was such that crack propagation was perpendicular to the rolling and parallel to the thickness direction of the 3.8–mm–thick plates. The one–third–size (3.33 x 3.33 x 25.4 mm) specimens were 30°– or 45°–notched, with root radii of 0.08 or 0.25 mm, respectively. Notch depth was kept constant at 0.61 mm.

Table 1. Elemental composition (impurities in wppm)[a] of laboratory (15–kg) heat of V–5Cr–5Ti and vanadium raw stock used to melt the ingot

Heat	Material	Spot	Cr	Ti	Al	Fe	Mo	Nb	Cu	Si	O	N	C	H	S	P	Ca	Cl	B
820630	raw V	–	<100	<50	100	230	410	<50	<50	780	200	62	75	3	10	<30	–	<2	<5
T87	V–5Cr–5Ti	top	4.96 wt.%	5.10 wt.%	160	150	520	<100	71	570	380	86	111	7	<20	<30	<17	<5	<5
		bottom	4.92 wt.%	5.03 wt.%	160	170	510	<100	63	520	380	93	107	27	<20	<30	<55	<5	<5

[a]Determined from ingot

RESULTS AND DISCUSSION

Charpy impact energies were measured between –196 and 200°C by an instrumented drop–weight machine. The effects of annealing temperature on impact properties of the 45°– and 30°–notched specimens are shown in Figs. 1 and 2, respectively. Some specimens in Fig. 1 were tested in as–rolled condition, i.e., without annealing (at 1000–1100°C) or after the customary degassing treatment (400°C for 1 h). The effects of annealing at 1000, 1050, and 1100°C (for 1 h in an ion–pumped vacuum) on impact properties of 30°–notched specimens are shown in Fig. 2. Also shown in the figure are data obtained on similar specimens annealed in the factory in an oil–diffusion–pumped vacuum at a nominal temperature of 1050°C for 2 h.

For impact temperatures <25°C, unannealed specimens were characterized by a tendency to exhibit laminated cracking parallel to the rolling direction and perpendicular to the thickness direction of the 3.8–mm–thick plate (from which the Charpy specimens were machined) (see Fig. 3). That is, the direction of the laminated cracking was perpendicular to the normal crack propagation of annealed specimens (Fig. 3A). As a result, relatively low absorbed energy was registered. However, the fracture surface of the laminated cracking was ductile in nature when examined by scanning electron microscopy (Fig. 3B). A similar mode of laminated cracking was observed in unannealed specimens from the 500–kg heat of V–4Cr–4Ti.[5] Although the mechanism of the peculiar laminated cracking is not well understood, these observations underscore the importance of proper annealing of the V–(4–5)Cr–(4–5)Ti alloy class.

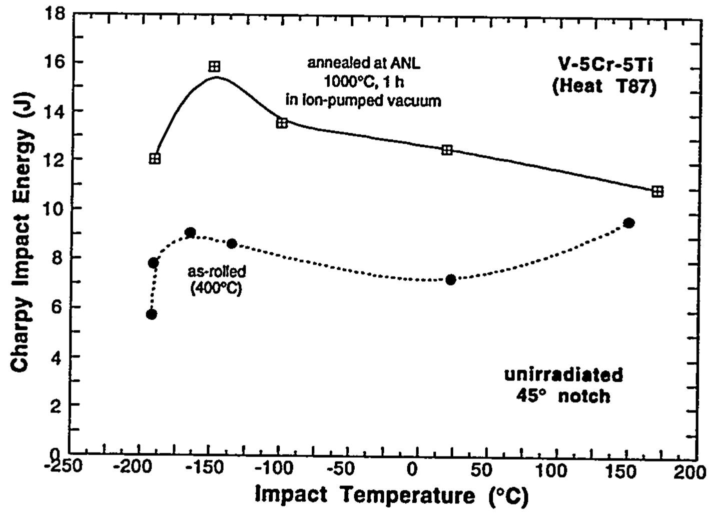

Fig. 1. Impact properties of 45°–notched Charpy specimens in as–rolled condition and after annealing at 1000°C for 1 h

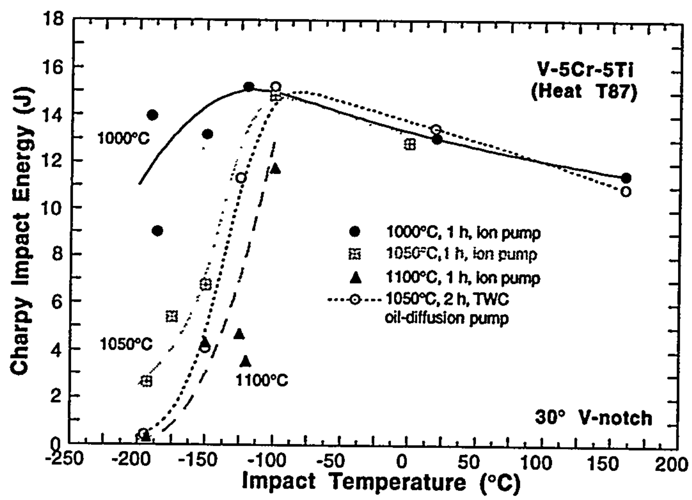

Fig. 2. Effect of annealing on impact properties of 30°–notched Charpy specimens

Absorbed energy measured at –196°C and ductile–brittle transition temperature (DBTT) of the heat were markedly sensitive to annealing temperature. This is shown in Figs. 4 and 5, respectively. Obviously, the results in Figs. 1–5 show that the optimal conditions for annealing are at 1000°C for 1 h in a high–quality (ion–pumped) vacuum system. Evidently, annealing at >1050°C is conducive to somewhat inferior impact properties. In Figs. 4 and 5, similar effects of annealing temperature on absorbed energy (measured at –196°C) and DBTT of the 500–kg heat of V–4Cr–4Ti are also shown for comparison. In the figures, it is important to note that sensitivity to annealing of impact properties of the two alloy heats is quite different. The laboratory heat of V–5Cr–5Ti is significantly more sensitive than production–scale heat of V–4Cr–4Ti. The 30–kg V–4Cr–4Ti (ANL ID BL–47) was least sensitive and Heat BL–63 of V–5Cr–5Ti was most sensitive to annealing conditions.[3] At present, the root cause of the heat–to–heat variation of sensitivity to annealing conditions is not well understood. Minor impurities, Cr content, or both could be contributing factors.

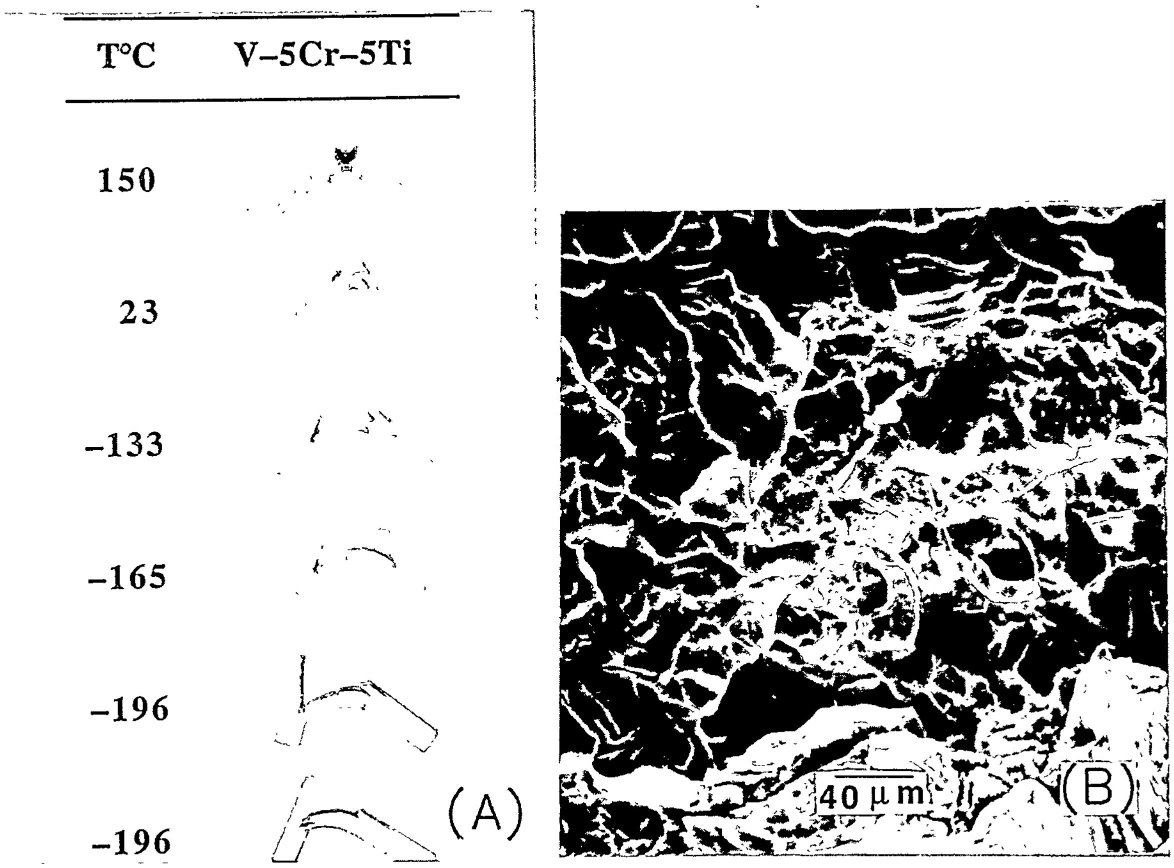

Fig. 3. Appearance of Charpy–impact specimens machined from as–rolled plates of V–5Cr–5Ti and tested at –196 to 150°C, showing (A) tendency for laminated cracking and (B) ductile nature of laminated fracture surface morphology, produced at 23°C

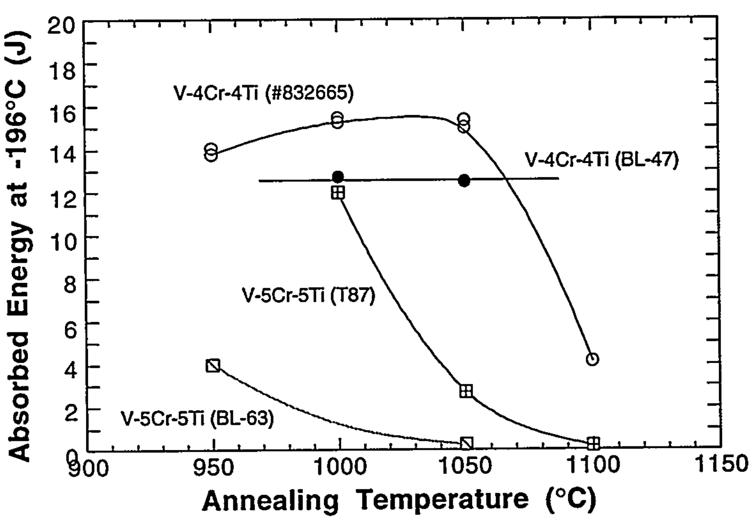

Fig. 4. Effect of annealing on Charpy absorbed energies of 15–kg V–5Cr–5Ti (#T87) and 500–kg V–4Cr–4Ti (#832665) measured at –196°C

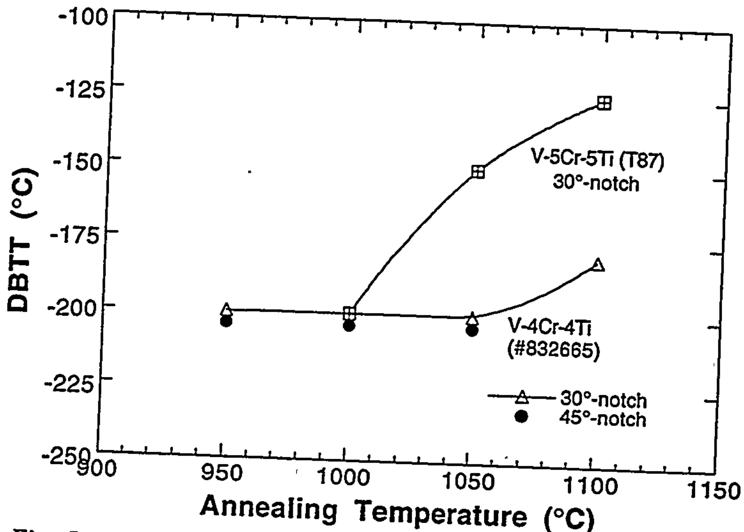

Fig. 5. Effect of annealing on DBTT of 15–kgV–5Cr–5Ti and 500–kg V–4Cr–4Ti

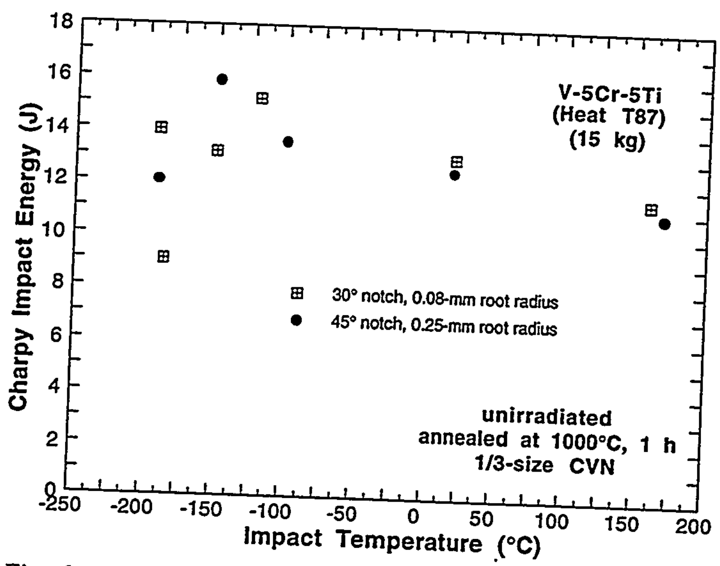

Fig. 6. Effect of notch geometry on Charpy impact properties of V–5Cr–5Ti laboratory heat annealed at 1000°C for 1 h

The effects of notch geometry on the impact properties of the laboratory heat, annealed under the optimal condition of 1000°C for 1 h are shown in Fig. 5. The results in the figure demonstrate that, when annealed properly, impact properties of V–5Cr–5Ti are not sensitive to notch geometry.

When annealed at the optimal condition, the impact properties of the unirradiated 15–kg laboratory heat of V–5Cr–5Ti and the 500–kg production–scale heat of V–4Cr–4Ti were essentially the same.[5] This means that, as long as a component is annealed properly, a sufficient tolerance of impact toughness to minor variations in alloying composition can be ensured for the V–(4–5)Cr–(4–5)Ti alloy class.

CONCLUSIONS

1. Impact properties were determined on a 15-kg laboratory heat of V-5Cr-5Ti, fabricated by the procedure that was followed to produce a 500-kg production-scale heat of V-4Cr-4Ti. After final annealing at 1000°C for 1 h, the laboratory heat of V-5Cr-5Ti exhibited impact properties as excellent as those of the production-scale heat of V-4Cr-4Ti, i.e., DBTT <-200°C and absorbed energies of 10-16 J. When annealed at 1050 or 1100°C, DBTT of the alloy increased to -175 and -125°C, respectively.

2. Unannealed as-rolled plates of V-(4-5)Cr-(4-5)Ti alloys are susceptible to laminated cracking parallel to the rolling plane, a mode of low-energy ductile fracture. Although the mechanism of the laminated cracking is not well understood, this study underscores the importance of proper annealing of this class of alloys.

3. Impact properties of some heats of V-(4-5)Cr-(4-5)Ti alloys are more sensitive to annealing than others. Although this significant heat-to-heat variation is not well understood, minor impurities are believed to play an important role.

4. Final annealing at 1000°C for 1 h in a high-quality vacuum is optimal for components fabricated from V-(4-5)Cr-(4-5)Ti alloys. When annealed at these conditions, excellent impact properties of the alloy class in unirradiated state can be ensured, regardless of minor variations in alloying-element composition.

REFERENCES

[1] D. L. Smith, B. A. Loomis, and H. M. Chung, Plasma Devices and Operations, Vol. 3, 1994, pp. 167-179.

[2] H. M. Chung, B. A. Loomis, and D. L. Smith, "Properties of V-4Cr-4Ti for Application as Fusion Reactor Structural Components," Fusion Eng. Design, 29 (1995), pp. 455-464.

[3] H. M. Chung, J. Gazda, L. Nowicki, J. E. Sanecki, and D. L. Smith, "Effects of Fabrication Variables on Impact Properties and Microstructure of V-Cr-Ti Alloys," in Fusion Reactor Materials, Semiannual. Prog. Report, DOE/ER-0313/15, Oak Ridge National Laboratory, Oak Ridge, TN (1994), pp. 207-218.

[4]. H. M. Chung, H.-C. Tsai, D. L. Smith, R. Peterson, C. Curtis, C . Wojcik, and R. Kinney, "Fabrication of 500-kg Heat of V-4Cr-4Ti," in Fusion Reactor Materials, Semiannual Prog. Report for Period Ending September 30, 1994, DOE/ER-0313/17, Oak Ridge National Laboratory, Oak Ridge, in press.

[5] H. M. Chung, L. Nowicki, and D. L. Smith, "Effect of Annealing on Impact Properties of Production-Scale Heat of V-4Cr-4Ti," in this report.