IMPACT PROPERTIES OF PRECRACKED V–4Cr–4Ti CHARPY SPECIMENS*

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OBJECTIVE

The objective of this study is to determine impact properties of production– and laboratory–scale heats of V–4Cr–4Ti, both fabricated and annealed with the same procedures, from precracked Charpy specimens.

SUMMARY

Laboratory– and production–scale (30 and 500 kg, respectively) heats of V-4Cr-4Ti, which is the reference vanadium alloy for application in fusion reactor structural components, have recently been produced successfully. Charpy tests conducted previously at –196 to 200°C on 1/3–size blunt–notch specimens, showed that both heats have excellent impact properties, i.e., ductile–brittle transition temperature (DBTT) lower than –200°C and upper–shelf energy of 10–16 J. Effects of precracking on the impact behavior of the Charpy specimens were investigated in this study. Precracked specimens were tested after annealing at the optimal condition of 1000°C for 1 h. Precracked specimens from both the laboratory– and production–scale heats exhibited normalized energies of 6.7 to 10.9 J at test temperatures of –196 to 200°C; no brittle fracture was observed. This demonstrates the excellent dynamic toughness of V–4Cr–4Ti.

INTRODUCTION

To develop and identify an optimal vanadium–base alloy for application in fusion reactor first wall/blanket structures, extensive investigations were conducted earlier on the swelling behavior, tensile properties, creep strength, impact toughness, and microstructural stability of V-Ti, V-Cr-Ti, and V-Ti-Si alloys before and after irradiation by fast neutrons at 420–600°C.[1–5] These investigations revealed that V-Cr-Ti alloys containing ≈4 wt.% Cr, ≈4 wt.% Ti, 500-1000 wt. ppm Si, and <1000 wt. ppm O+N+C were most desirable because they exhibit superior physical and mechanical properties. Excellent impact properties were reported previously for laboratory– and production–scale heats,[6] including a small heat (ANL ID BL–47, 30–kg) that exhibited excellent resistance to thermal creep,[4] irradiation–induced embrittlement,[1,2] swelling,[3,5] and helium embrittlement.[7–10]

However, no impact properties have been reported for precracked Charpy specimens of either heat. Precracked Charpy impact properties are generally considered a better measure of dynamic toughness of a material because without the complication of crack initiation in such a test, absorbed energy represents the resistance to crack propagation more accurately than in a blunt–notch specimen. In this work, impact behavior of fatigue–precracked Charpy specimens of the laboratory– (30–kg, ANL ID BL–47) and production–scale (Heat 832665)[11] heats of V–4Cr–4Ti was investigated according to ASTM Standard E23 (Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, Annex A1, Precracking Charpy V–Notch Impact Specimens).

EXPERIMENTAL PROCEDURE

Chemical composition of the 30– and 500–kg heats of V–4Cr–4Ti is given in Table 1. One–third–size Charpy specimens (3.33 x 3.33 x 25.4 mm) were machined from 3.81–mm–thick plates of the materials, which had been received in as–rolled condition. The specimens were machined so that the plane of crack propagation was perpendicular to rolling direction (L–S and L–T directions, Fig. 1). However, directions of precracking, and hence the direction of crack propagation during impact testing of the

* Work supported by U.S. Department of Energy, Office of Fusion Energy Research, under Contract W-31-109-Eng-38.

production– and laboratory–scale heats, were different, i.e., in thickness and width direction of the plate, respectively. By this selection of specimen orientation, we wished to determine any effect of anisotropic crack propagation in the alloy.

Table 1. Chemical composition (impurities in wppm) of production– and laboratory–scale heats of V–4Cr–4Ti

Heat ID	Heat Type	Cr	Ti	Cu	Si	O	N	C	S	P	Ca	Cl	Na	K	B
BL–47	laboratory 30 kg	4.1 wt.%	4.3 wt.%	6	870	350	220	200	20	<40	1	1	0.1	0.1	15
832665	production 500 kg	3.8 wt.%	3.9 wt.%	<50	783	310	85	80	<10	<30	<10	<2	–	–	<5

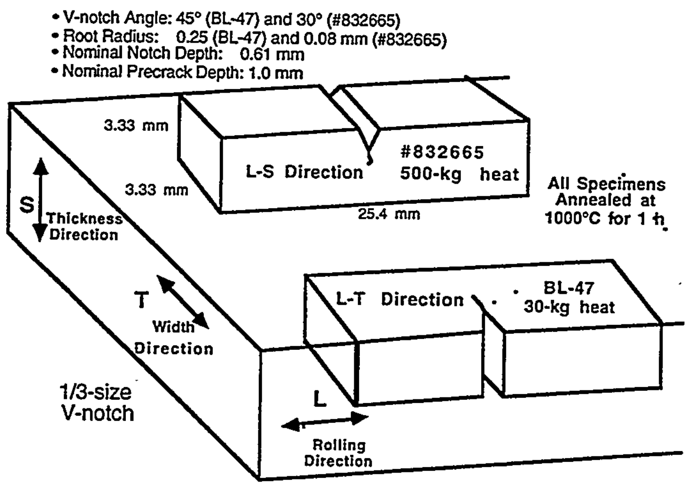

Fig. 1. Orientation of precracked Charpy–impact specimens with respect to plate rolling direction of V–4Cr–4Ti

Notch depth in both types of specimens was kept constant at 0.61 mm. The impact specimens, machined from the as–rolled plates and precracked by cyclic fatigue, were tested after an annealing heat treatment at 1000°C for 1 h in ion–pumped vacuum, the optimal annealing procedure identified in a separate study.[7] Details of the drop–weight–type impact test are described in Ref. 2.

The machined blunt–notch specimens were precracked by three–point bending with an MTS servo–hydraulic mechanical test system fitted with a 454–kg (1000–lb) load cell and interfaced with a computer system to operate the system under constant stress intensity. Precracking was induced by cyclic fatigue loading of the specimen between a maximum stress intensity $K_{max} = 10$ MPa $m^{0.5}$ and a minimum stress intensity $K_{min} = 0.1\ K_{max}$. That is, maximum stress intensity and stress ratio were kept constant at 10 MPa $m^{0.5}$ and 0.1 (R = 0.1), respectively. Crack length was monitored continuously by the direct current potential difference technique, enabling stress intensity to be controlled as a function of crack length. Typical initial and final loading were 365 and 169 N, respectively. To produce a crack depth of 0.9–1.0 mm, the typical numbers of 200,000–240,000 and 18,000–210,000 cycles were required for the production– (Heat 832665) and laboratory–scale (BL–47) heats, respectively.

RESULTS AND DISCUSSION

Typical examples of the precracking morphology, and the fracture appearance (produced during impact testing) of the production– and laboratory–scale heats, are shown in Figs. 2A and 2B, respectively.

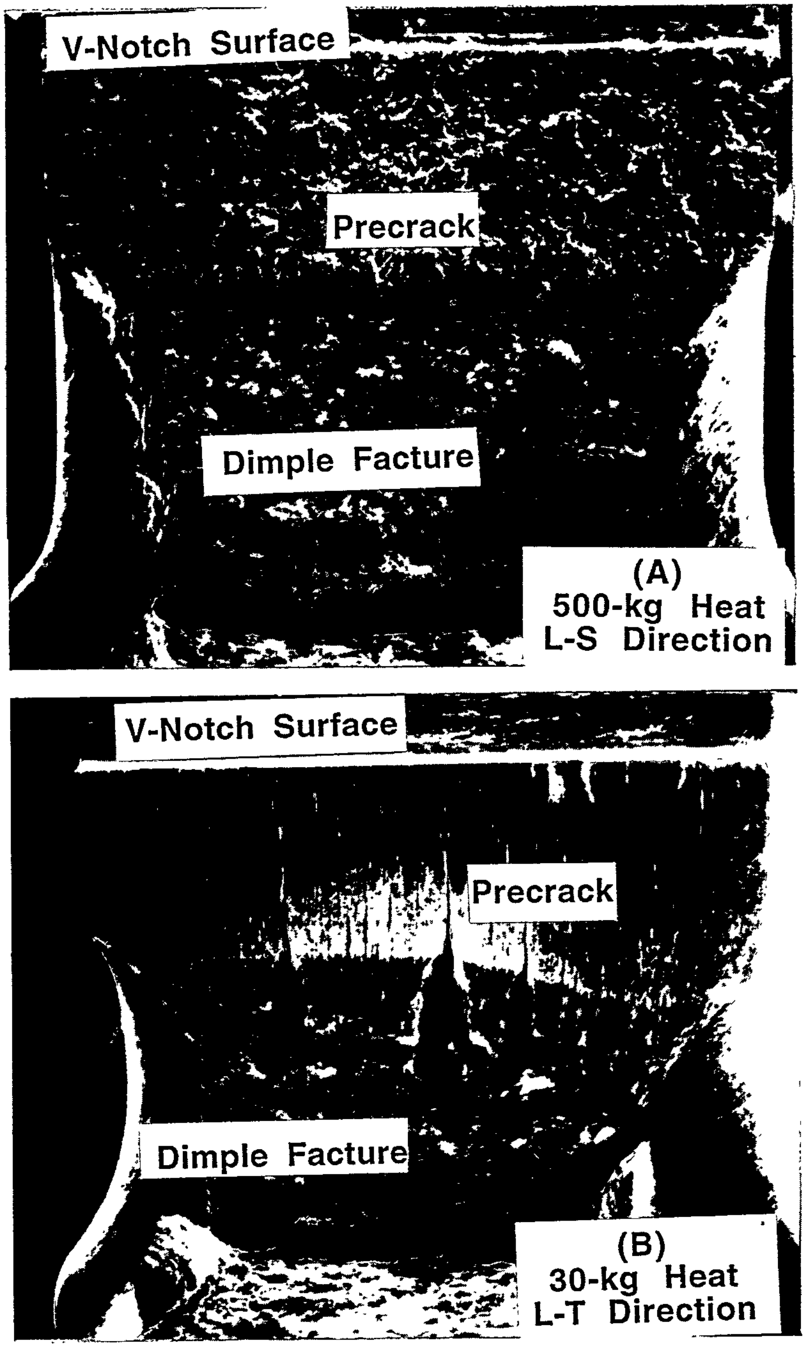

Fig. 2. Appearance of precracking and impact–fracture surfaces in (A) production–scale heat (#832665) tested at –150°C; and (B) laboratory–scale heat (BL–47) tested at 21°C

In the figures, three distinct types of surfaces, i.e., machined V–notch, precracking, and dimple fracture, are clearly visible. In contrast to the production–scale heat, precracking produced in the laboratory heat was characterized by a relatively nonuniform crack front. This is most likely related to the difference in the orientation of the specimens of the two heats (Fig. 1). Small and shallow secondary cracks are also visible on the precracking surface of the laboratory heat (Fig. 2B). These secondary cracks, perpendicular to the direction of the primary precracking, are indeed parallel to the rolling plane of the 3.8–mm–thick plate from which the Charpy specimens were machined. This observation seems to be consistent with the tendency for unannealed plates of V–(4–5)Cr–(4–5)Ti alloys to develop low-energy laminated cracking in exactly the same direction.[12]

From examination of fractured precracked specimens similar to those shown in Fig. 2, combined crack lengths (V-notch plus precrack depth) were measured at three locations on each specimen per ASTM Standard E 23, and absorbed impact energies were normalized relative to the remaining uncracked cross section of each specimen. Results are listed in Table 2. Also reported in Table 2 are fractions of ductile and brittle-cleavage fracture surface morphologies for each specimen. No brittle cleavage was observed in specimens tested after annealing at 1000°C for 1 h. In contrast, a few specimens tested after annealing at 1100°C for 1 h exhibited limited brittle cleavage at <–170°C. This observation seems to corroborate the selection of the optimal annealing condition at 1000°C for 1 h for both V–4Cr–4Ti[7] and V–5Cr–5Ti.[12]

Table 2. Summary of combined notch and precracking depths and normalized absorbed energies measured in precracked Charpy impact specimens of production-scale (500-kg, #832665) and laboratory (30-kg, BL-47) heats of V-4Cr-4Ti, measured after impact fracture per ASTM E-23.

Heat ID	PCVN ID	Final Anneal[a] Temp. (°C)	Impact Temp. (°C)	Crack Length Left (mm)	Crack Length Center (mm)	Crack Length Right (mm)	Crack Length Average (mm)	Absorbed Energy (J)	Normalized Energy (J)	Ductile Dimple Fracture (%)	Brittle Cleavage Fracture (%)
BL-47	A10	1000	-196	1.28	1.49	1.76	1.52	3.66	6.73	100	0
BL-47	A12	1000	-150	1.55	1.49	1.48	1.51	4.01	7.34	100	0
BL-47	A9	1000	-100	1.50	1.50	1.67	1.56	5.22	9.82	100	0
BL-47	A11	1000	21	1.50	1.64	1.72	1.62	5.37	10.46	100	0
832665	W42	1000	-196	1.65	1.66	1.65	1.65	4.34	8.60	100	0
832665	W46	1000	-150	1.61	1.63	1.62	1.62	5.59	10.89	100	0
832665	W36	1000	-100	1.58	1.60	1.56	1.58	4.86	9.25	100	0
832665	W52	1000	21	1.67	1.69	1.70	1.69	3.68	7.47	100	0
832665	W49	1000	175	1.64	1.64	1.62	1.64	3.62	7.13	100	0
832665	W43	1100	-194	1.67	1.64	1.62	1.64	1.84	3.63	60	40
832665	W33	1100	-175	1.69	1.68	1.67	1.68	5.41	10.92	90	10

[a]Annealed for 1 h in ion-pumped high vacuum.

The normalized energies for the production- and laboratory-scale heats listed in Table 2 are plotted as function of impact temperature in Figs. 3 and 4, respectively. For comparison, similar results obtained from blunt-notch specimens are also plotted in the figures. In Fig. 5, all impact data of both heats of V–4Cr–4Ti alloy, obtained from blunt-notch and precracked specimens annealed at 950–1050°C for 1 h, are shown for a comprehensive comparison.

The results in Figs. 3–5 demonstrate that remarkably excellent dynamic toughness of V–4Cr–4Ti will be ensured when a component fabricated from the alloy is given a final annealing treatment at 1000 ± 50°C for 1 h. When annealed at 1000°C for 1 h, precracked specimens of the laboratory and production heats, machined in two different orientations (Fig. 1), displayed essentially the same impact properties (Fig. 5); this indicates the negligible effect of anisotropic crack propagation.

CONCLUSIONS

(1) After annealing at 1000°C for 1 h, impact tests were conducted on precracked 1/3-size Charpy specimens of 30-kg laboratory-scale and 500-kg production-scale heats of V–4Cr–4Ti. Both heats exhibited excellent impact properties, i.e., normalized energies of 6.7 to 10.9 J at test temperatures of –196 to 200°C. No brittle-cleavage fracture morphology was observed in the precracked specimens. This demonstrates the excellent dynamic toughness of V–4Cr–4Ti.

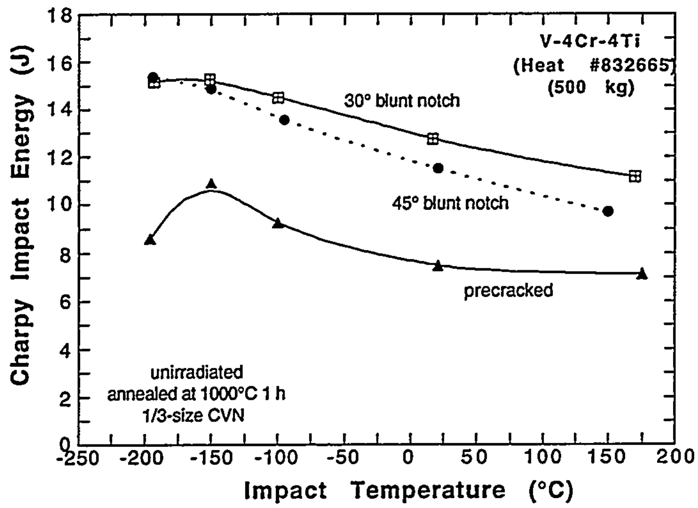

Fig. 3.
Precracked and blunt–notch Charpy energy as a function of impact temperature of production–scale heat of V–4Cr–4Ti after annealing for 1 h at 1000°C

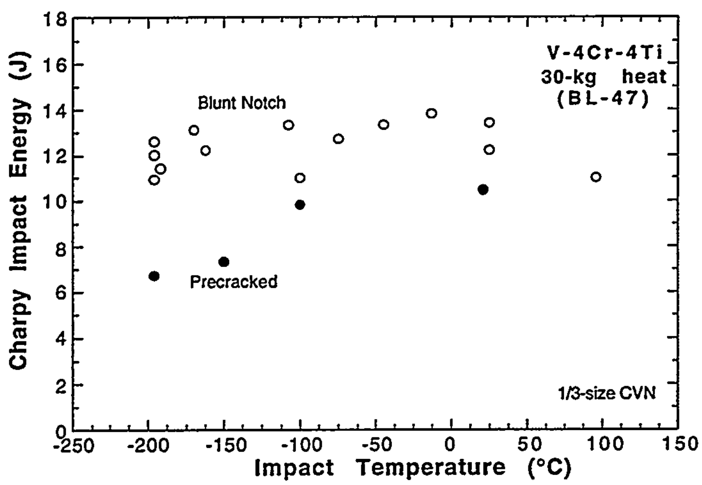

Fig. 4.
Precracked and blunt–notch Charpy energy as a function of impact temperature of laboratory–scale heat of V–4Cr–4Ti. Precracked and blunt–notch specimens were annealed for 1 h at 1000°C and ≈1050°C, respectively

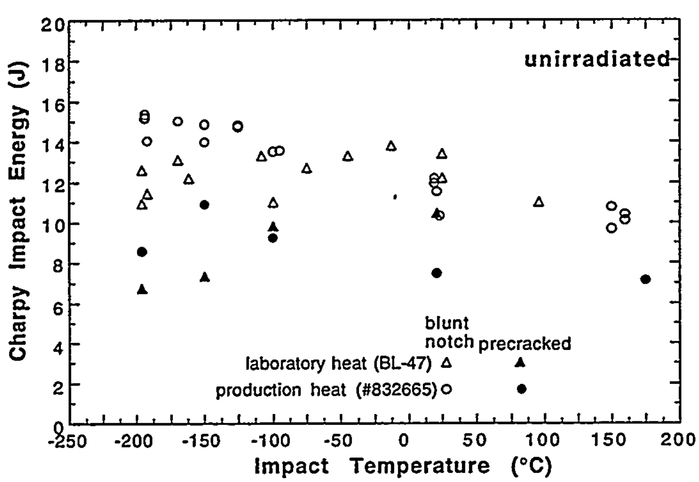

Fig. 5.
Impact properties measured from blunt–notch and prec–racked Charpy specimens of the production– and labor–atorys cale heats ofV–4Cr–4Ti.

(2) Annealing at 1100°C for 1 h induced limited cleavage fracture in precracked specimens at test temperatures <–170°C. This corroborates the selection of the optimal annealing condition of 1000°C for 1 h.

(3) When annealed at 1000°C for 1 h, impact properties of precracked specimens of two different orientations were similar, indicating the negligible effect of anisotropic crack propagation.

ACKNOWLEDGMENTS

The authors thank J. K. Donald and D. Busch for precracking the Charpy–impact specimens and SEM fractography, respectively.

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