IMPACT PROPERTIES OF 500–kg HEAT OF V–4Cr–4Ti* H. M. Chung, L. Nowicki, J. Gazda, and D. L. Smith, (Argonne National Laboratory)

OBJECTIVE

Following previous reports of excellent properties of a laboratory heat of V–4Cr–4Ti, the alloy identified as the primary vanadium–based candidate for application as fusion reactor structural components, a large industrial–scale (500–kg) heat of the alloy was fabricated successfully. The objective of this work is to determine the impact properties of the industrial–scale heat.

SUMMARY

A 500-kg heat of V-4Cr-4Ti, an alloy identified previously as the primary vanadium–based candidate alloy for application as fusion reactor structural components, has been produced successfully. Impact tests were conducted at –196°C to 150°C on 1/3–size Charpy specimens of the scale–up heat after final annealing for 1 h at 950, 1000, and 1050°C. The material remained ductile at all test temperatures, and the ductile–brittle transition temperature (DBTT) was lower than –200°C. The upper–shelf energy of the production–scale heat was similar to that of the laboratory–scale (≈15–kg) heat. Effect of annealing temperature was not significant; however, annealing at 1000°C for 1 h produced impact properties slightly better than those from other annealing treatments. Effect of notch geometry was also investigated on the heat. Under otherwise similar conditions, DBTT increased ≈30°C when the notch angle was reduced from 45° (root radius 0.25 mm) to 30° (root radius 0.08 mm).

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°C–600°C. These investigations revealed that V-Cr-Ti alloys containing ≈4 wt.% Cr, ≈4 wt.% Ti, 400-1000 wt. ppm Si, and <1000 wt. ppm O+N+C were most desirable because they exhibit superior physical and mechanical properties.[1–6] These results were obtained, however, on laboratory–scale (<30–kg) heats, including a small heat (ANL ID BL–47) of V-4Cr-4Ti that exhibited excellent resistance to thermal creep,[4] irradiation–induced embrittlement,[1,2] swelling,[3,5] and helium embrittlement.[7–9] In this reporting period, a large (≈500–kg) industrial–scale heat of V–4Cr–4Ti (Heat ID 832665) was fabricated successfully in a joint effort between Argonne National Laboratory and Teledyne Wah Chang (Albany, Oregon) with the objective of demonstrating reliable industrial production of good–quality V–4Cr–4Ti.[10] This report describes results of metallographic examination and Charpy–impact testing of the 500–kg heat. The Charpy–impact test (at –196°C to 150°C) was chosen because it has been shown to be most sensitive to the quality of vanadium–base alloys.

EXPERIMENTAL PROCEDURE

Chemical composition of the 500–kg heat is given in Table 1. Also in the table is the chemical composition of the laboratory–scale heat of V–4Cr–4Ti (ANL ID BL–47) that was shown earlier to exhibit excellent properties.[1–9]

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One–third–size Charpy specimens (3.33 x 3.33 x 25.4 mm) were machined from 3.81–mm–thick plates of the material, some of which had been annealed for 2 h at a nominal temperature of ≈1050°C and some of which had been received in as–rolled (at 400°C) condition. The Charpy specimens were machined so that the plane of crack propagation was perpendicular to rolling direction. To investigate the effect of notch geometry, two types of V–notch geometry were investigated; one with a 45° notch angle and 0.25–mm root radius and the other with a 30° angle and 0.08–mm root radius. Notch depth in both types of specimens was kept constant at 0.61 mm. The specimens machined from as–annealed plates were heat–treated at 400°C for 1 h in a vacuum of ≈6 x 10^{-4} Pa prior to impact testing, a customary procedure used to expel hydrogen that could be picked up during specimen machining and preparation. To identify the optimal annealing condition, specimens machined from as–rolled (cross–rolled at 400°C)[10] plates were annealed at 950°C and 1000°C for 1 h in a vacuum of ≈6 x 10^{-6} Pa prior to testing. Details of the drop–weight–type impact test have been described elsewhere.[2]

Table 1. Chemical composition (impurities in wppm) of industrial– (500 kg) and laboratory–scale heats of V–4Cr–4Ti.

Heat ID	ANL ID	Heat Type	Cr	Ti	Cu	Si	O	N	C	S	P	Ca	Cl	Na	K	B
–	BL–47	laboratory, 15 kg	4.1 wt.%	4.3 wt.%	6	870	350	220	200	20	<40	1	1	0.1	0.1	15
832665	BL–71	production, 500 kg	3.8 wt.%	3.9 wt.%	<50	783	310	85	80	<10	<30	<10	<2	–	–	<5

RESULTS AND DISCUSSION

Charpy energies, measured on the production–scale heat of V–4Cr–4Ti after annealing for 1 h at 950, 1000 and 1050°C, are shown in Fig. 1 as a function of impact temperature. All specimens in the figure had a notch angle of 45° and a root radius of 0.25 mm, the same geometry used in previous investigations.[2] From the results in the figure, the optimal annealing temperature appears to be ≈1000°C, the same as that found to produce minimum hardness in ≈85% cold–worked V–4Cr–4Ti (i.e., the smaller laboratory heat BL–47, Table 1).[11] Results in Fig. 1 show that the impact properties of the production–scale heat are as good as those of the smaller laboratory heat, which was vacuum–arc melted. The DBTT of the production heat is no higher than ≈–200°C, similar to that of the laboratory heat. To show a direct comparison, Charpy energies of the two heats are plotted in Fig. 2.

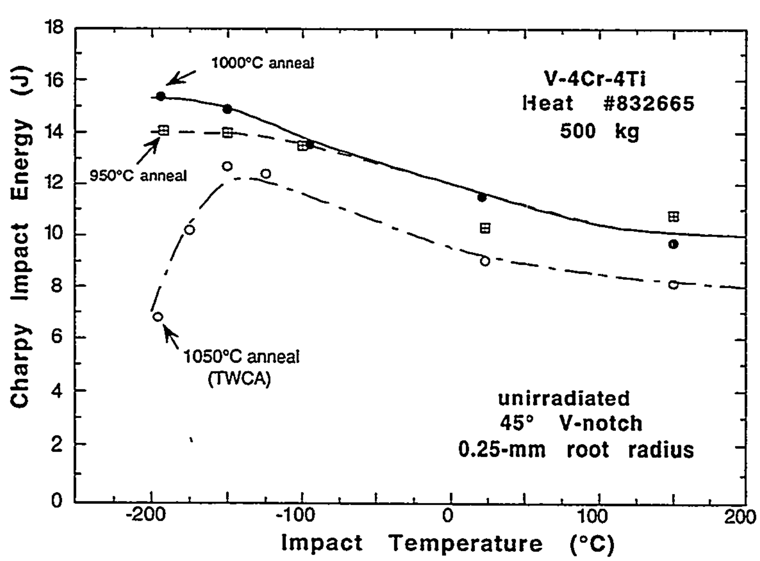

Figure 1. Charpy energy as function of impact temperature of production–scale V–4Cr–4Ti heat after annealing for 1 h at 950, 1000, and 1050°C. Optimal anneal–ing temperature is ≈1000°C.

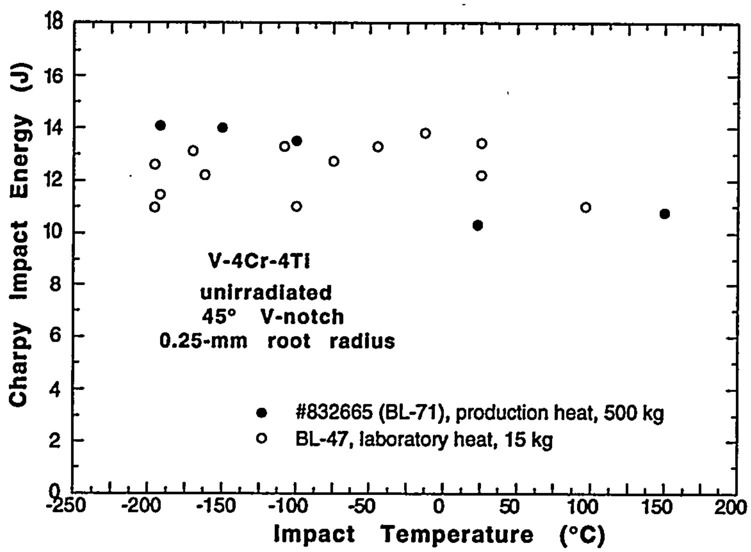

Figure 2. Comparison of impact properties of the production– and laboratory–scale heats of V–4Cr–4Ti.

Grain structures of the specimens annealed at 950, 1000, and 1050°C are shown in Fig. 3. After annealing at ≈1050°C (for 2 h at Teledyne Wah Chang), most of the material seems to have been fully recrystallized, exhibiting an average grain size of ≈28 µm (Fig. 3C). The material was hardly recrystallized after annealing either at 950°C or 1000°C. When examined under polarized light, etched specimens of the alloy annealed at 950°C revealed what appears to be a lath-shaped, gold-colored secondary phase (the light-contrasted feature denoted by arrows in Fig. 3A). Volume fraction of the phase was negligible, however, when annealed at 1000°C (Fig. 3B). Although the nature of the phase could not be identified at this time, precipitation of the secondary phase does not appear to influence the impact properties significantly.

Effect of notch geometry is shown in Fig. 4. Specimens (average grain size ≈28 µm) in the figure were annealed at a nominal temperature of 1050°C for 2 h at Teledyne Wah Chang. When notch angle and root radius were decreased from 45° to 30° and 0.25 to 0.08 mm, respectively, DBTT increased from ≈–200°C to ≈–170°C, whereas maximum energy decreased from ≈13 to ≈10.5 J. Similar tests of the effect of notch geometry are being conducted on specimens annealed at the optimal temperature of 1000°C.

CONCLUSIONS

(1) Impact tests were conducted on production–scale (≈500-kg) heat of V-4Cr-4Ti at –196°C to 150°C. Results showed that the material remained ductile at –196°C and that the ductile–brittle transition temperature (DBTT) was no higher than –200°C. Upper–shelf energies of the production–scale heat were similar to those of the laboratory–scale heat.

(2) Effect of annealing temperature (950, 1000, and 1050°C) on impact properties of the production–scale heat was not significant, a finding similar to that of the laboratory–scale heat. This is in contrast to the very significant effect of annealing temperature on the impact properties of one heat of V–5Cr–5Ti produced by an incorrect process and found to exhibit inferior mechanical properties. Annealing at 1000°C for 1 h produced optimal impact properties in the production–scale heat of V–4Cr–4Ti that are slightly better than those from other annealing treatments.

(3) When the V–notch angle and root radius were decreased from 45° to 30° and from 0.25 to 0.08 mm, respectively, DBTT increased from ≈–200°C to ≈–170°C, whereas maximum energy decreased from ≈13 to ≈10.5 J.

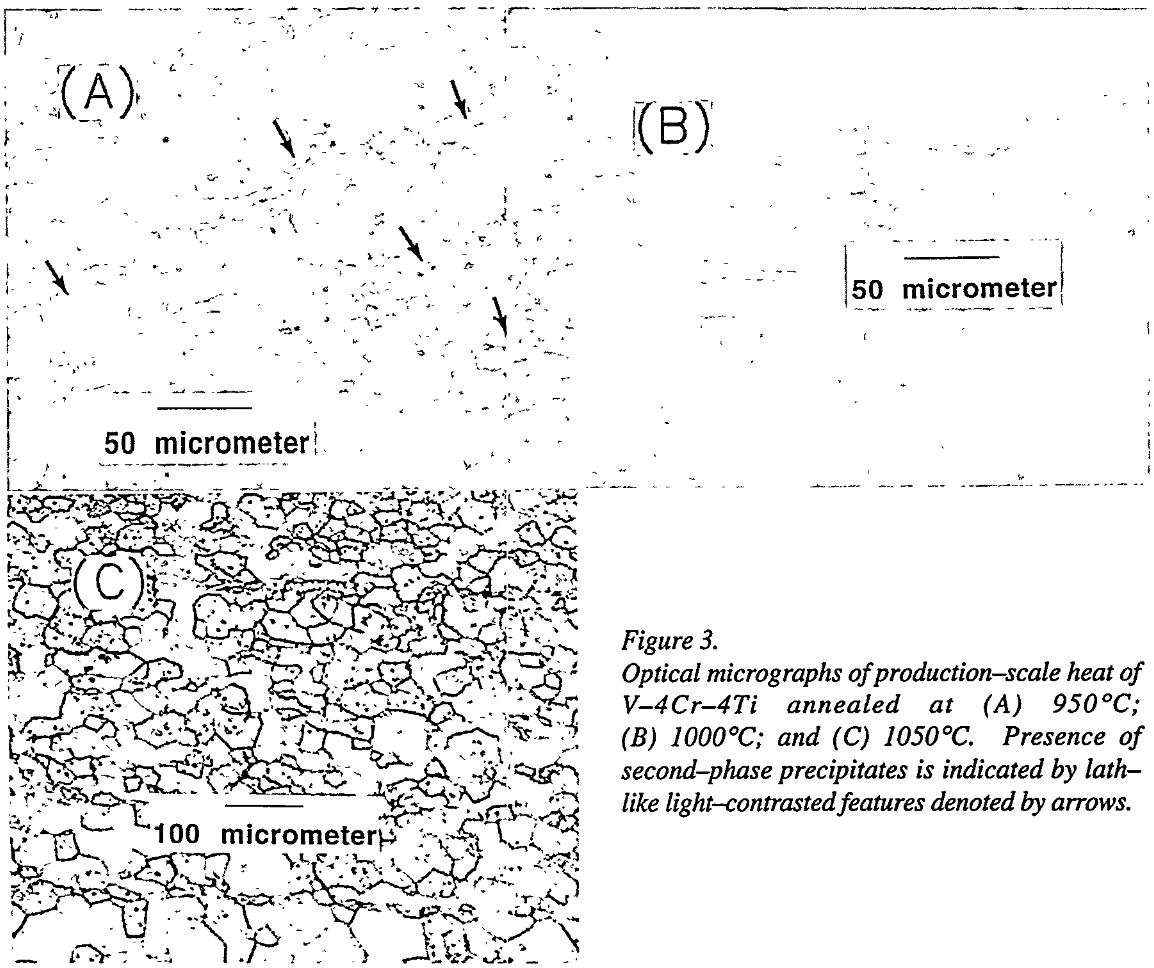

Figure 3.
Optical micrographs of production–scale heat of V–4Cr–4Ti annealed at (A) 950°C; (B) 1000°C; and (C) 1050°C. Presence of second–phase precipitates is indicated by lath–like light–contrasted features denoted by arrows.

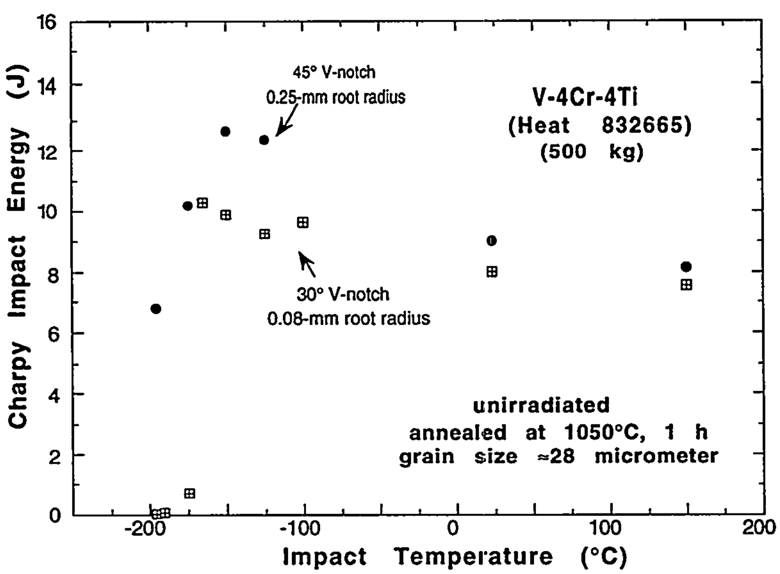

Figure 4.
Effect of notch geometry on impact properties of the production–scale heats of V–4Cr–4Ti.

ACKNOWLEDGMENT

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