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Thomas I. Jones
Donald J. Sandstrom

LOS ALAMOS NATIONAL LABORATORY
3 9338 00365 1931

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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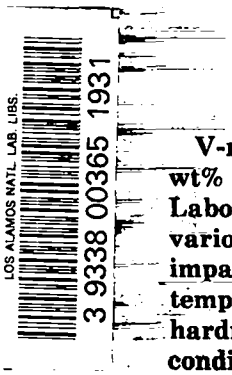


ABSTRACT

V-notch Charpy impact specimens were machined from U-0.75 wt% Ti penetrator cores supplied by the Air Force Armament Laboratory. The response of these specimens to impact loads at various temperatures was measured. The data indicated that the impact energy required to cause fracture was a function of temperature and appeared to be insensitive to microstructural and hardness variations. All tests from −54 to 300°C indicated a brittle condition with data fitting the impact energy = $4.41e^{0.0048t}$ equation.

INTRODUCTION

The Air Force Armament Laboratory (AFAL) at Eglin Air Force Base, FL, became concerned when a larger than normal scatter in the penetration vs non-penetration data points occurred during testing of U-0.75 wt% Ti penetrators. A possible explanation was that the scatter might be related to the range of temperatures within which the material changed from primarily ductile to brittle behavior. AFAL asked the Los Alamos Scientific Laboratory (LASL) to perform a series of tests to determine the ductile to brittle transition temperature of high-density U-0.75 wt% Ti penetrator cores and the penetration performance of cores tested above and below this temperature.

TESTS AND RESULTS

We inspected the as-received penetrator cores for surface cracks and corrosion. We found no surface cracks and only very thin adherent surface corrosion.

Chemical analyses were made on four selected penetrator cores and Charpy samples. Table I lists the titanium, carbon, hydrogen, nitrogen, and oxygen concentrations as well as spectrographic analyses of trace elements. The hydrogen contents were considered high for good-quality uranium alloys. All other element concentrations were considered normal for this alloy.

Standard V-notch Charpy bars were machined from the penetrator cores. These Charpy bars conformed to the full-size test specimen dimensions listed in ASTM designation A370, Methods and Definitions for Mechanical Testing of Steel Products.

The tests were conducted at −54, 23, 74, 100, 200, and 300°C. No tests were made above 300°C because the alloy can be aged in the 350 to 400°C range. Testing in this range might have changed the properties of the as-received material. We obtained the −54°C temperature using alcohol and dry ice. The 74 and 100°C tests were made using heated silicone oil. The 200 and 300°C tests were made using an argon gas filled oven. Only slight oxidation of the impact specimens was observed from the heating mediums. A minimum of five samples were tested at each of the four lower temperatures. We believe the lower temperature range was of the greatest ballistic interest. Three samples were tested at each of the two highest temperatures. All tests met the ASTM requirements.

The impact energy data obtained from this investigation are listed in the Appendix. LASL statisticians evaluated the data and found that the best fit was obtained by the following equation: impact energy (IE) in joules = $4.41e^{0.0048t}$, where e is the natural logarithm and t is the temperature. Figure 1 shows the plot of the above equation. Of the 28 data points observed, only 1 fell outside the 95%

TABLE I

CHEMICAL AND SPECTROCHEMICAL ANALYSES OF U-0.75 WT% Ti PENETRATORS

Element[a]	Specimen 1 (ppm)	Specimen 2 (ppm)	Specimen 3 (ppm)	Specimen 4 (ppm)
Ti[b]	0.80	0.76	0.77	0.77
C	10	5	5	15
H	4.0	3.5	2.5	2.7
N	4	14	12	20
O	40	35	35	40
Al	25	18	12	12
Cu	18	18	18	18
Fe	50	35	35	35
Ni	25	25	25	25
Pb	50	35	35	35
Si	85	95	95	85

[a]All other analyzed impurities were 5 ppm or below the present detection limits.

[b]Quantities for this element are in percent.

prediction limits.* This point was at −54°C and outside the upper limit. If the alloy composition and processing history were similar, the curve generated by the equation could be used to predict impact values at temperatures up to 300°C.

Figure 2 shows the fracture surface profiles of Charpy bar halves tested at (1) room temperature, (2) 100°C, (3) 200°C, and (4) 300°C. The 200°C specimen shows very small shear lips, whereas the 300°C specimen shows a somewhat larger shear lip. The presence of these shear lips is indicative of a slight emergence from the very brittle condition. *All* of the specimens tested, including those tested at 300°C, were considered to be in the brittle condition, as defined by impact strength and fractography.

Metallographic examinations were made on broken Charpy pieces from each of the test temperatures. Scanning electron microscopy (SEM) of the fracture surfaces was used in addition to optical microscopy of the bulk alloy, except for the specimens tested at 300°C. In the 300°C tests, the fracture surfaces oxidized before the broken pieces could be immersed in a protective medium. The broken halves of Charpy bars were mounted such that the structure from the notch to the side impacted was examined by optical microscopy. Figures 3 through 8 are photomicrographs of the Charpy bar structures.

Figure 3a shows a structure that was overaged. Figure 3b shows the brittle, cleavage fracture of this specimen tested at −54°C.

Figures 4a and b show a structure just past the optimum aging peak on one side of the specimen, whereas Figs. 4c and d show a structure on the opposite surface that represented a more overaged condition. The diamond pyramid hardnesses (DPH) generally confirmed this observation. The appearance of these two structures in the proximity of a penetrator core suggests a difference in quenching rate from the solution treatment temperature across this sample. Figure 4e again represents a brittle, cleavage fracture.

Figures 5a and b also show a variation in microstructure indicative of a variable quenching rate and subsequent variation in the response of the materials to the thermal aging treatment. Hardness values confirmed this trend to overaging and subsequent softening. Figure 5c shows a very thin ductile zone at the notch, as evidenced by the ductile dimple structure that changed abruptly to cleavage fracture.

Figures 6a, b, and c were similar to previous specimens, that is, an overaged structure and a thin

*A 95% prediction interval is the interval where 95% of all the individual ordinate values (impact) should lie for a given abscissa value (temperature). This differs from a 95% confidence interval in that it is an interval where 95% of the means (of a large number of ordinate values) should lie for a given abscissa value.

ductile band at the notch changing to cleavage fracture over a preponderance of the fracture.

Figures 7a and b represent a structure with very little overaging. Figure 7c shows the entire width of the ductile zone at the notch, and Fig. 7d shows a higher magnification view. Figure 7e shows the transition from ductile to brittle fracture.

Figures 8a and b also show the range of structures found on one specimen.

SUMMARY

Metallographic examinations of the penetrator cores revealed structures varying from an estimated near-optimum aging to some that were greatly overaged. The hardnesses varied widely, showing some correlation with structure within a particular sample but bearing no absolute relationship from one sample to another. The specimens tested at above room temperature revealed thin fracture zones of a ductile appearance near the notch, but the bulk of all fracture surfaces examined had a brittle appearance.

The data obtained from the impact tests indicate that the impact energy required to cause fracture is a function of temperature and appears to be insensitive to the microstructural and hardness variations observed in this series of specimens. We concluded that the U-0.75 wt% Ti penetrator cores tested were in the brittle condition at test temperatures up through 300°C.

This observation is supported by the good fit of the data to the derived formula $IE = 4.41e^{0.0048t}$, which relates impact energy to temperature only, with no correlation to variations in microstructure. The insensitivity of impact strength to structure is anomolous with general metallurgical experience.

ACKNOWLEDGMENTS

We appreciate the encouragement and support of this investigation by the Air Force Armament Laboratory, Air Force Systems Command, Eglin AFB, FL.

We thank James Gray for his assistance with the impact tests, James Bradberry and Charles Javorsky for the metallography, Harry Martz for the statistical analysis, and LASL Group CMB-1 for the analytical results.

APPENDIX
IMPACT ENERGY DATA

INDIVIDUAL IMPACT ENERGY VALUES

Test Temperature (°C)	Impact Energy Individual Values (J)	Average (J)
−54	4.7, 2.7, 3.7, 2.7, 2.7	3.3
23	5.4, 4.1, 4.7, 5.4, 5.4	5.0
74	6.8, 6.8, 6.8, 5.4, 6.1, 6.8	6.4
100	6.8, 5.7, 6.4, 6.4, 6.1, 7.5	6.5
200	12.2, 12.9, 12.9	12.7
300	16.9, 18.2, 19.7	18.3

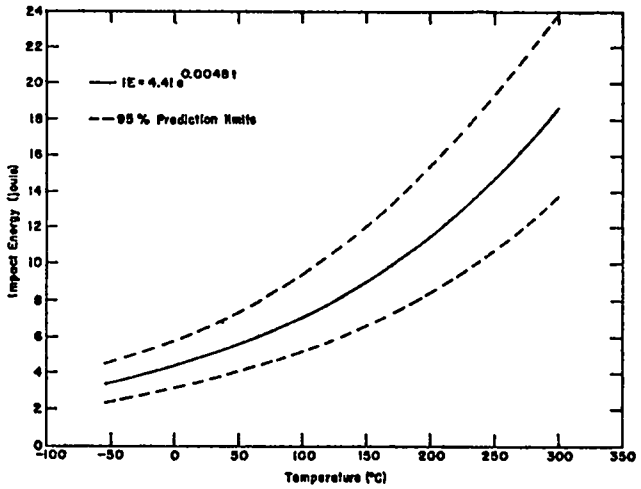


Fig. 1.
Impact energy vs temperature for U-0.75 wt% Ti penetrators.

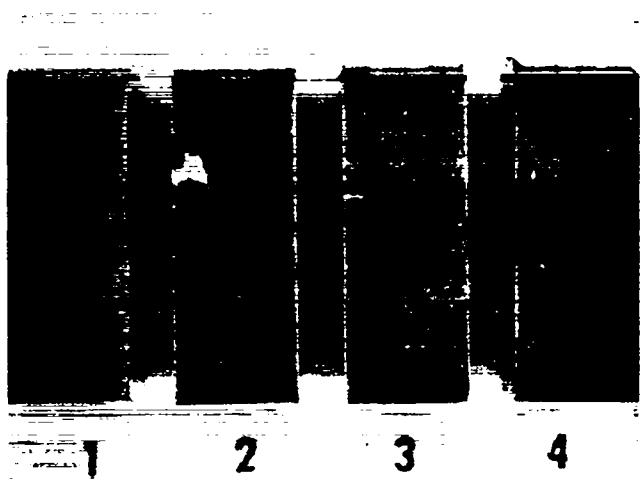
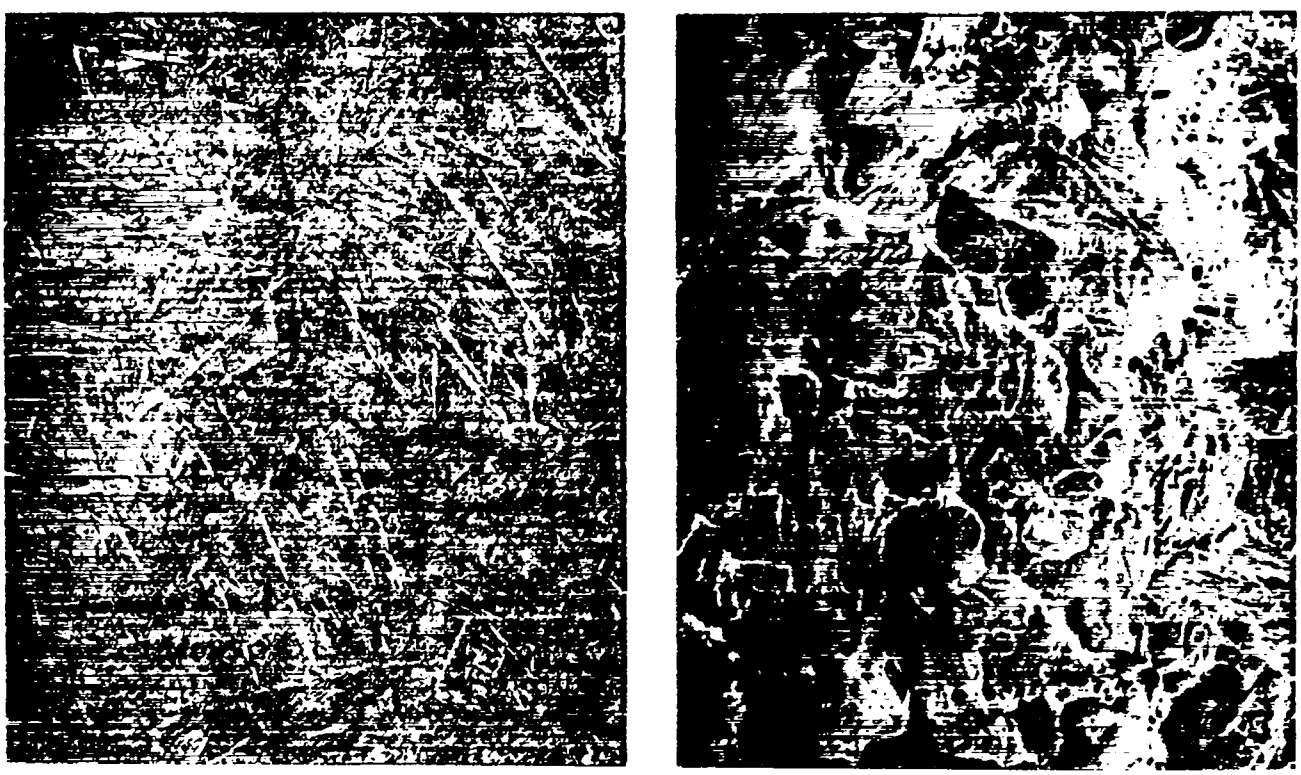


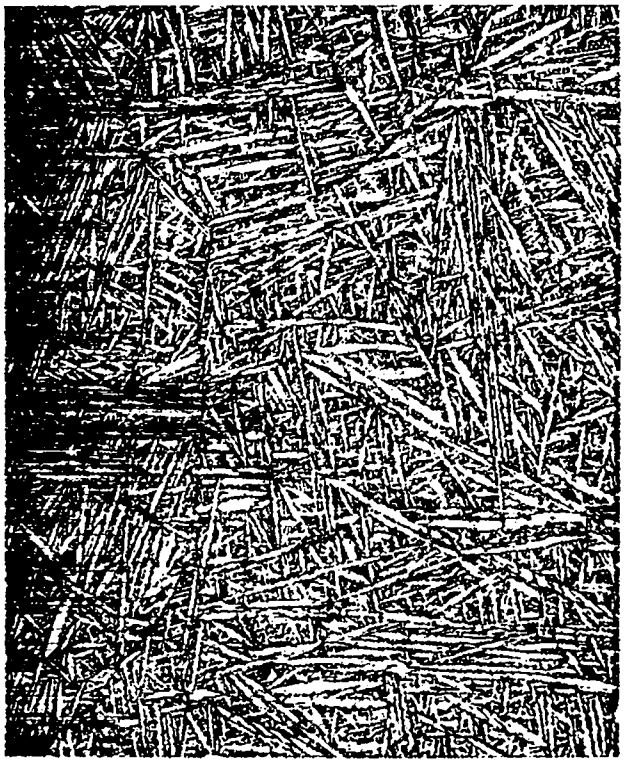
Fig. 2.
Broken Charpy bar profiles.



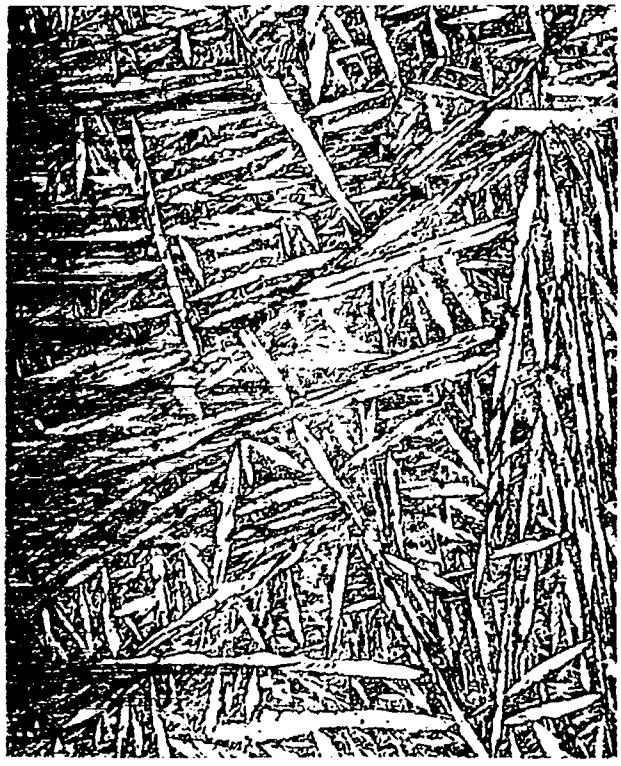
a. Optical, 100X, 470 DPH

b. SEM, 700X

Fig. 3.
Charpy bar tested at −54°C.

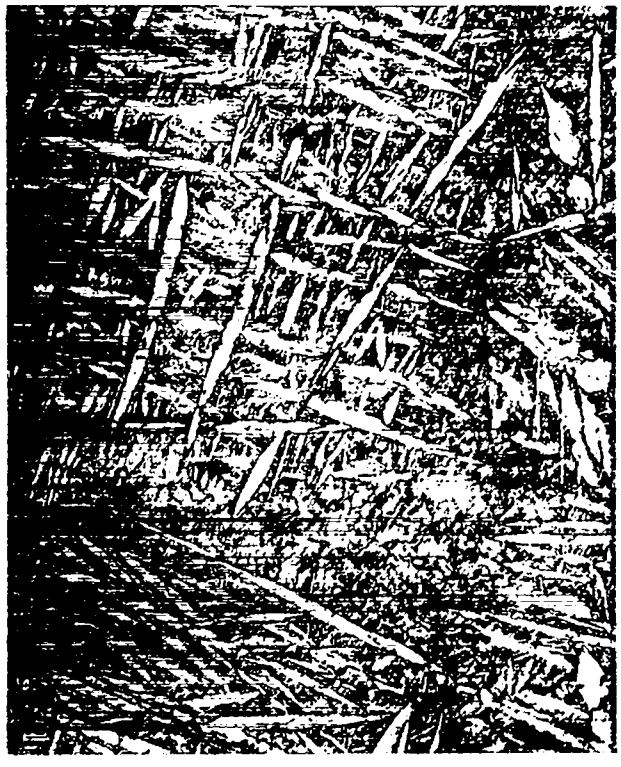


a. Optical, 100X, side 1, 450 DPH



b. Optical, 250X, side 1

c. Optical, 100X, side 2, 430 DPH



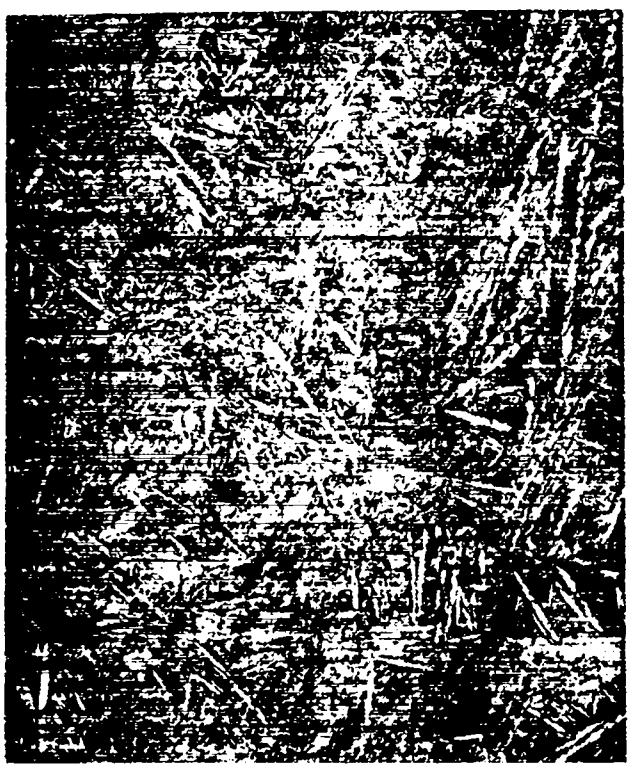
d. Optical, 250X, side 2

Fig. 4.
Charpy bar tested at 23°C.

e. SEM, 700X

a. Optical, 100X, side 1, 490 DPH

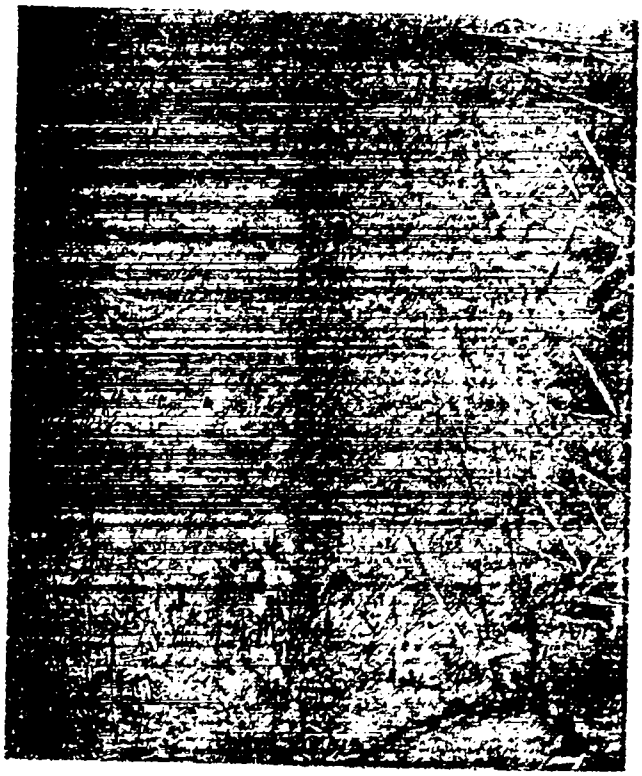
Fig. 4.
Continued.



b. Optical, 100X, side 2, 465 DPH

c. SEM, 700X

Fig. 5.
Charpy bar tested at 74°C.



a. Optical, 100X, 465 DPH

b. SEM, 700X

c. SEM, 2000X

Fig. 6.
Charpy bar tested at 100°C.

a. Optical, 100X, 460 DPH

b. Optical, 250X

Fig. 7.
Charpy bar tested at 200°C.

c. SEM, 700X

d. SEM, 1000X

e. SEM, 1000X

Fig. 7.
Continued.

a. Optical, 100X, side 1, 475 DPH

b. Optical, 100X, side 2, 435 DPH

Fig. 8.
Charpy bar tested at 300°C.