Irradiation study of Ti-6Al-4V and Ti-6Al-4V-1B for FRIB beam dump: Experimental plan

Aida Amroussia, PhD Student
Chemical Engineering and Materials Science
Michigan State University
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Motivation

- Study of irradiation damage in Ti-6Al-4V and Ti-6Al-4V-1B
- Irradiation with different particles and energy levels:
  - Neutron
  - Heavy ions with low, intermediate and high energy

Compare the results:

Does boron addition improves mechanical properties of Ti-6Al-4V after irradiation?

Are the changes in mechanical properties of the Ti-alloys "similar" after neutron and heavy ions irradiation? At what neutron flux ? What energy/ intensity/ dpa rate?

Ti-6Al-4V vs Ti-6Al-4V-1B

Boron addition improves different characteristics of Ti-6Al-4V:

- The stability of the microstructure is increased.
- The specific stiffness and strengths increases to 50%.
- Improvement of the machinability and thermo-mechanical processing is obtained.

Alloy		Ti-6Al-4V	Ti-6Al-4V-1B
E [GPa]	At RT	110	127
	At 500 °C	90	113
Yield Stress [MPa]	At RT	1000	1190
	At 500 °C	450	663
Ultimate Tensile Strength [MPa]	At RT	827	1300
	At 500 °C	430	785
Minimum creep rate [s^{-1}]	T=500, 400 MPa	$1.24.10^{-6}$	$5.89.10^{-8}$
HCF strength [MPa]	At 500 °C	172-258	314-471

Chen, W., C.J. Boehlert, E.A. Payzant, and J.Y. Howe. "The Effect of Processing on the 455°C Tensile and Fatigue Behavior of Boron-modified Ti–6Al–4V." *International Journal of Fatigue* 32, no. 3 (March 2010): 627–638.

Wei Chen and Carl J. Boehlert, 'Characterization of the Microstructure, Tensile and Creep Behavior of Powder Metallurgy Processed and Rolled Ti-6Al-4V-1B Alloy', *Key Engineering Materials*, 436 (2010), 195–203

Literature review of neutron irradiation damage in Ti-6Al-4V:

Tensile and fracture toughness

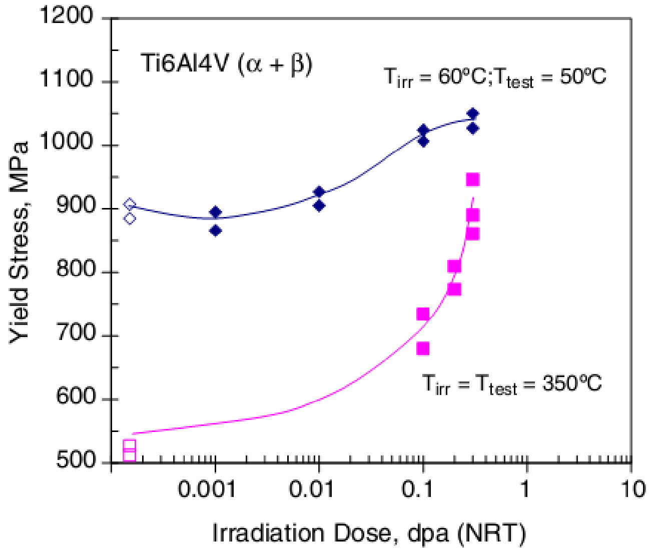


Fig. 3. Dose dependence of yield strength of Ti6Al4V alloy at different temperatures. Open symbols correspond to unirradiated conditions.

- **Yield strength saturates at irradiation doses higher than 0.3 dpa at 60°C.**
- **No saturation at 350°C**

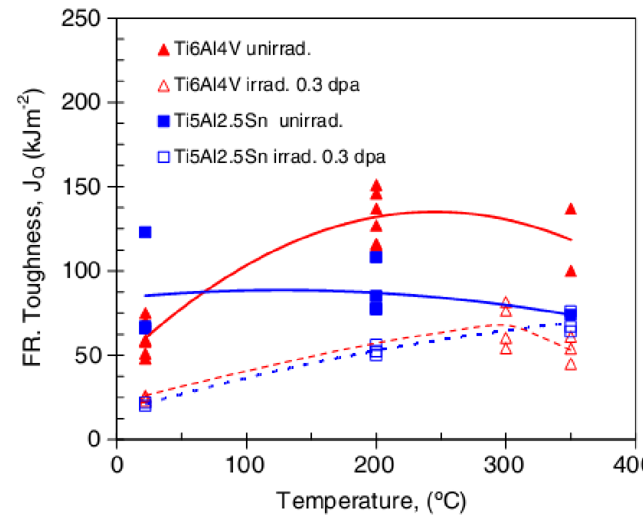


Fig. 5. Initiation fracture toughness values for Ti6Al4V and Ti5Al2.5Sn alloy in unirradiated conditions and neutron irradiated to a dose level of 0.3 dpa at different temperatures.

Different hardening mechanisms operate at 50°C than at 350°C.

S. Tähtinen, P. Moilanen and B.N. Singh, 'Effect of Displacement Dose and Irradiation Temperature on Tensile and Fracture Toughness Properties of Titanium Alloys', Journal of Nuclear Materials, 367-370 (2007), 627–632

Literature review of neutron irradiation damage in Ti-6Al-4V:

Microstructure

Temperature and dose level	Microstructure change observations
50^{o}C , 0.3 dpa	A high density of uniformly distributed defect clusters in the α-phase No changes in the overall dislocation or phase structures
350^{o}C, 0.3 dpa	Dislocation loops Vanadium precipitates
450^{o}C Dose 2.1 and 32 dpa	Dislocation loops β-phase precipitates in α phase
550^{o}C 32 dpa	Extensive void formation Coarse β-precipitates

S. Tähtinen, P. Moilanen and B.N. Singh, ‘Effect of Displacement Dose and Irradiation Temperature on Tensile and Fracture Toughness Properties of Titanium Alloys’, Journal of Nuclear Materials, 367-370 (2007), 627–632

Irradiation and post-irradiation characterization plan:

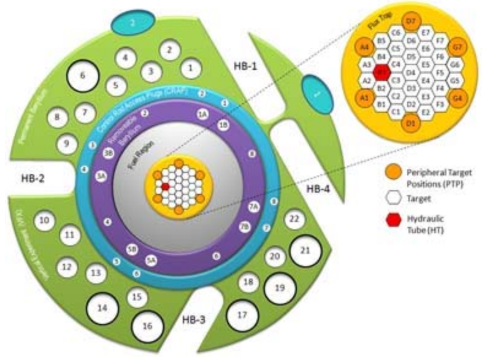
1. Neutron irradiation
2. Heavy ion irradiation

1. Neutron irradiation

- Abundance of data on neutron irradiation of Ti-6Al-4V (low doses)
- Comparison between Ti-6Al-4V and Ti-6Al-4V-1B

Reference	Irradiation Facility	Reactor	Atmosphere	Temperature	Neutron fluence	Dose
[1]	Institute of Reactor Materials, Russia	IVV-2M reactor	inert gas	250 C	unkown	0.2 and 0.3 dpa
[2]	Risø National Laboratory, Denmark	DR-3 reactor	atmosphere of helium	50 C and 350 C	1.5 10^24 n/m2 (E > 1 MeV)	0.3 dpa
[3]	Atomic Energy Research Institute in Budapest	VVRSZM Russian Research Reactor	Cooling through He/N2 gas	150 C	1.08E20 n/cm2 (E > 1 MeV)	0.15 dpa

1. Neutron irradiation at HFIR-ORNL



Irradiation experiment:

- Neutron flux =1E+14n/cm^2/sec, for E>0.183 MeV.
- Irradiation time: 1 cycle (23 days)
- Sample: 0.76 x 1.52 x 7.6 mm
- Temperature : 350 C

Post irradiation characterization :

- The Materials Science and Technology Division of ORNL is equipped with remote hot cells with servo-hydraulic test systems that can perform mechanical testing:
  - Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM) and Atom Probe Tomography (APT) to perform microstructural characterization.
  - In-situ tensile testing and fracture toughness testing machines to study the mechanical properties of the neutron irradiated Ti-6Al-4V-1B.

2. Heavy ion irradiation:

I. Low energy irradiation at CIMAP-GANIL France

ion	energy MeV/nucleon	minimum current (µAe)	flux min (ions/(cm².s))	required time (1UT=8 hours)	Range in the material (µm)
Ar	1	15 µAe	10^{12}	12	8

	IRRSUD – Ar 36	FRIB – O 18	FRIB – Ca 48	FRIB – U 238
Energy (MeV/A)	1	230	194	156
Estimated dpa/h	0.3	$2.5.10^{-5}$	$2.5.10^{-4}$	$1.5.10^{-3}$
Total dose	-	0.13	1.35	8.5
Se (keV/nm)	7.24	0.08	0.6	12.6

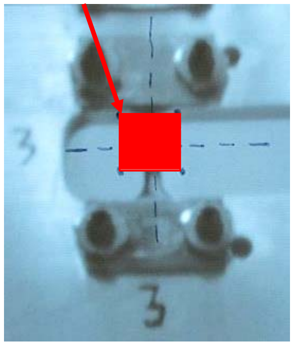
Table 1 – Comparison between IRRSUD and FRIB beams

2. Heavy ion irradiation:

I. Low energy irradiation at CIMAP-GANIL France

- Irradiation experiment:
- Samples : Dogbone samples (550-800µm)and TEM samples
- Temperature : 350 C and RT
- Material: Ti-6Al-4V and Ti-6Al-4V -1B
- Post-irradiation characterization at MSU:
  - In-situ tensile tests
  - Nano-indentation
  - TEM and SEM characterization
  - X-Ray diffraction (small angle diffraction)

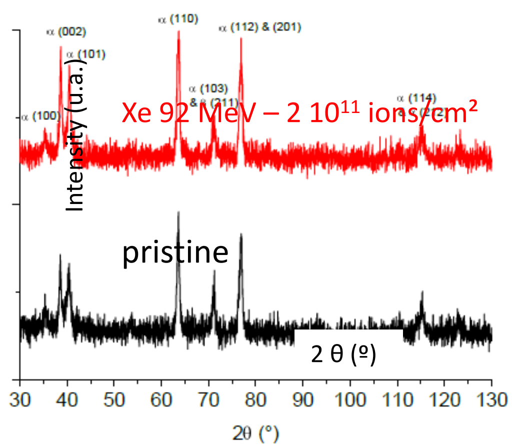
Beam area

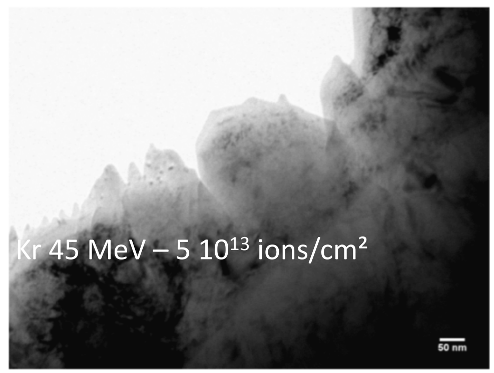


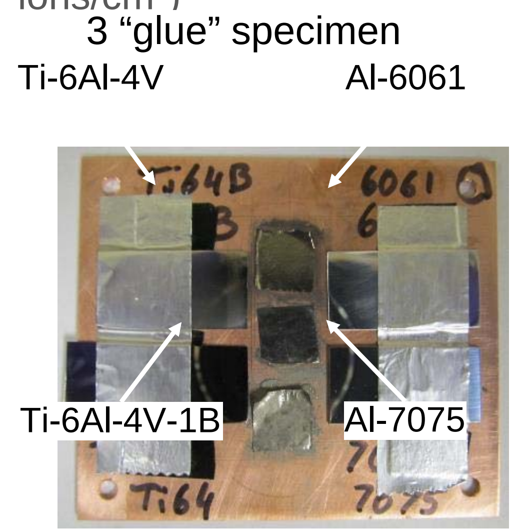
Dogbone samples

Preliminary results with Ti-6Al-4V

- Two tests were performed at IRRSUD - CIMAP in July and October 2013 with both Ti-alloys (Ti-6Al-4V and Ti-6Al-4V-1B)
  - 4 irradiations (^{82}Kr at 25 and 45 MeV and ^{131}Xe at 92 MeV, up to 2.5 10^{15} ions/cm²)







- No evidence of phase transformation and ion track in Ti-6Al-4V promises good radiation resistance of this alloy

2. Heavy ion irradiation:

II. Intermediate energy irradiation at ATLAS- Argonne

	A	E total (MeV)	E (MeV/u)	Range (µm)	Se (keV/nm)	I (pnA)	P (W)	Dose rate Dpa/day
Ar	40	660	16.50	150	2.75	1000		2
Kr	84	1201	14.30	96	10.18	500	416	4

Post-irradiation characterization: Hot cells at Irradiated material Lab

- Tensile testing - Fracture toughness - Fatigue
- TEM / TEM
- The LECO machines for measuring oxygen, nitrogen and hydrogen contents of the irradiated samples.

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- References

[1]Rodchenkov, B.S., M.V. Evseev, Yu.S. Strebkov, L.P. Sinelnikov, and V.V. Shushlebin. "Properties of Unirradiated and Irradiated Ti–6Al–4V Alloy for ITER Flexible Connectors." *Journal of Nuclear Materials* 417, no. 1–3 (October 2011)

[2]Tähtinen, S., P. Moilanen, B. N. Singh, and D. J. Edwards. "Tensile and Fracture Toughness Properties of Unirradiated and Neutron Irradiated Titanium Alloys." *Journal of Nuclear Materials* 307 (2002): 416–420.

[3]Hegedüs, Ferenc, Roland Brütsch, Brian Oliver, and Pierre Marmy. *Fracture Toughness and Tensile Properties of the Titanium Alloys Ti6A14V and Ti5A12. 5Sn Before and After Proton and Neutron Irradiations at 150° C*. Centre de recherches en physique des plasmas (CRPP), Ecole polytechnique fédérale, 2004.