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

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

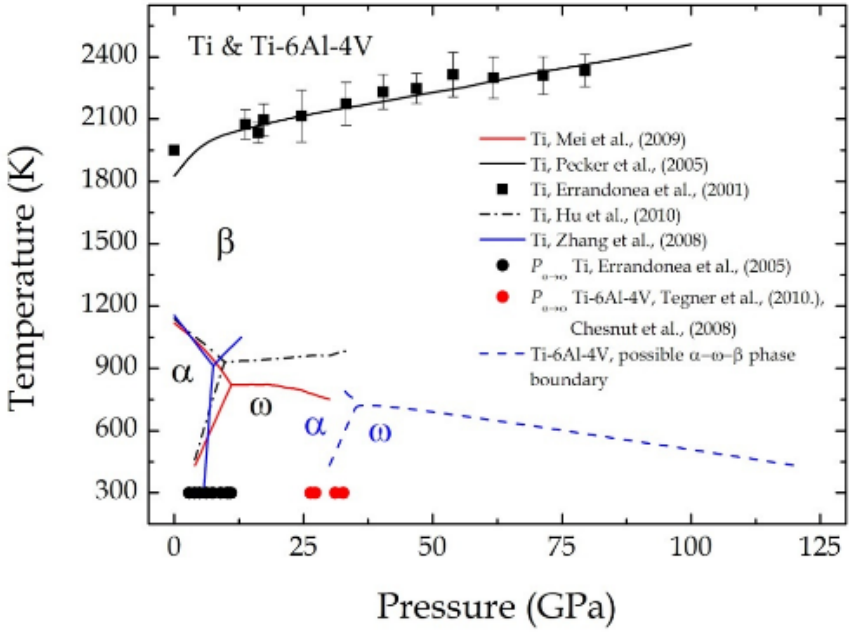
- Irradiation of samples with high energy heavy ions (NSCL-MSU)(Ca 40 @ 2000 MeV) and low energy heavy ions at CIMAP-France
- XRD and TEM observations(in collaboration with CIMAP)
- Surface characterization using SEM-EBSD
- Nano-indentation tests
- Vickers Hardness tests
- Insitu-tensile tests

Irradiation experiments

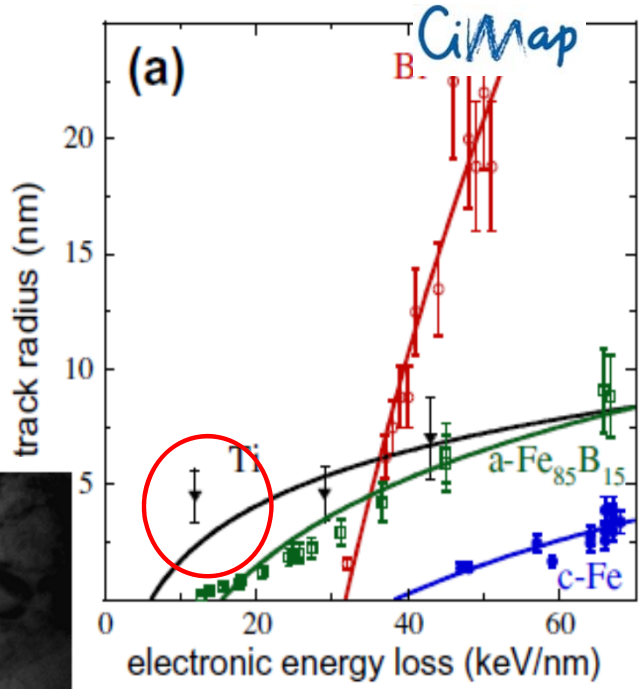
Facilities	Beam	Energy [MeV]	Range [µm]	S_e [keV/nm]	Fluence [ions/cm²]	Max dpa in sample	Date	Number of samples	Type
IRRSUD	^{82}Kr	25	4.73	9.9	5.10^{11}-5.10^{12}-2.10^{14}	0.6	Jul-13	6	Foils
IRRSUD	^{131}Xe	92	8.5	19.7	2.10^{11}	0.001	Jul-13	2	Foils
IRRSUD	^{82}Kr	45	6.43	13.1	5.10^{11}-5.10^{13}	0.16	Jul-13	4	Foils
IRRSUD	^{82}Kr	45	6.43	13.1	2.10^{14} $2.5.10^{15}$	8	Oct-13	6	Foils
IRRSUD	^{36}Ar	36	6.8	7.5	10^{15}	1.5	Dec-13	23	TEM and dogbone
IRRSUD	^{129}Xe	92	8.5	19.7	If 3 10^{14} (~10h)	Estimated 1.7	Planned in June-2014		
NSCL	^{40}Ca	2000	800	1.5	6 10^{12}	10^{-5}	Aug-13	1 x Ti64	Dogbone

XRD and TEM observations(in collaboration with CIMAP)

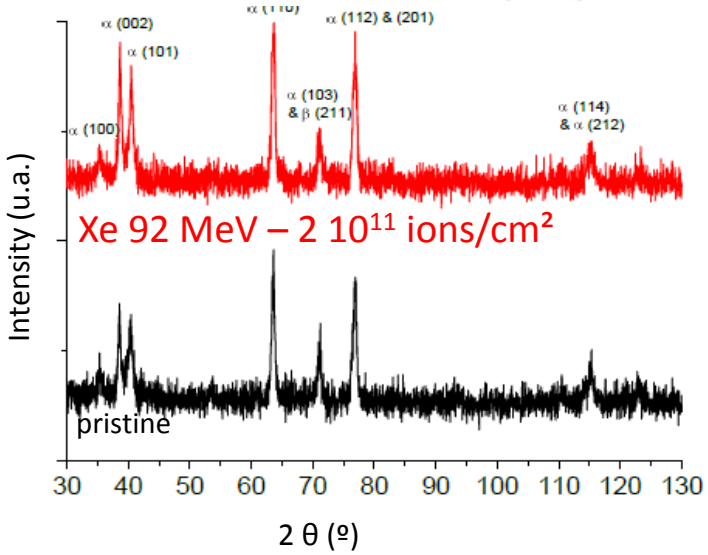
- No evidence of phase transformation or ion track formation in Ti-6Al-4V

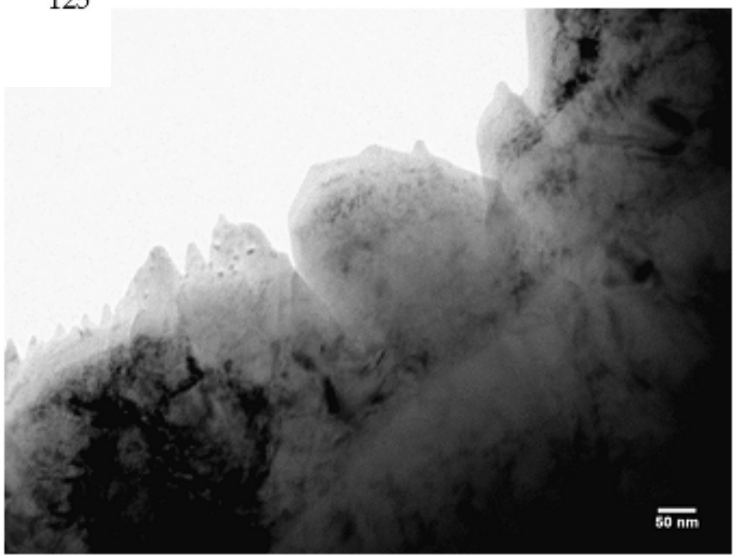


Ti-alloys are not sensitive to electronic excitation by swift heavy ions compared to pure Titanium



M. Toulemonde et al./ NIMB 277 (212) 28-39





TEM image of a Ti-6Al-4V foil irradiated with Kr 45 MeV – 5 10¹³ ions/cm²

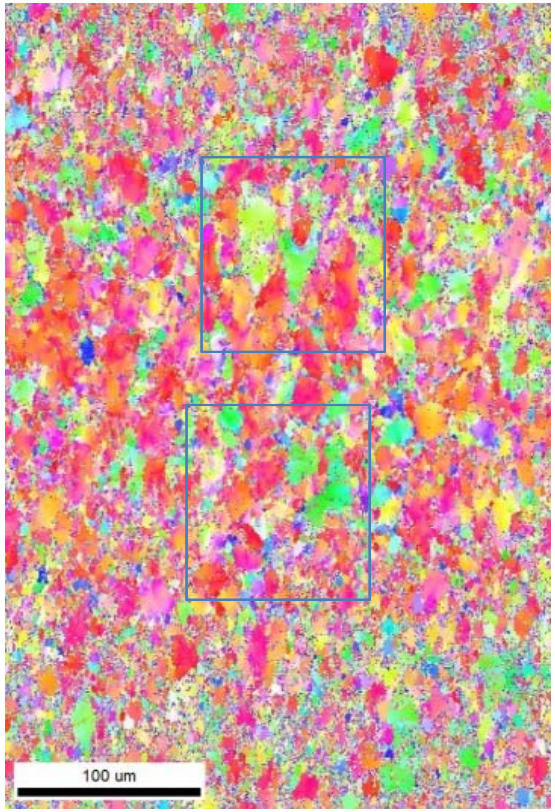
Characterization of the microstructure and mechanical properties:

- Scanning electron microscopy (SEM) as well as electron backscatter diffraction (EBSD) were used to characterize the microstructure of the samples before and after irradiation.
- Nano-indentation , Vickers Hardness and in-situ tensile tests were used to investigate the change in the mechanical properties.

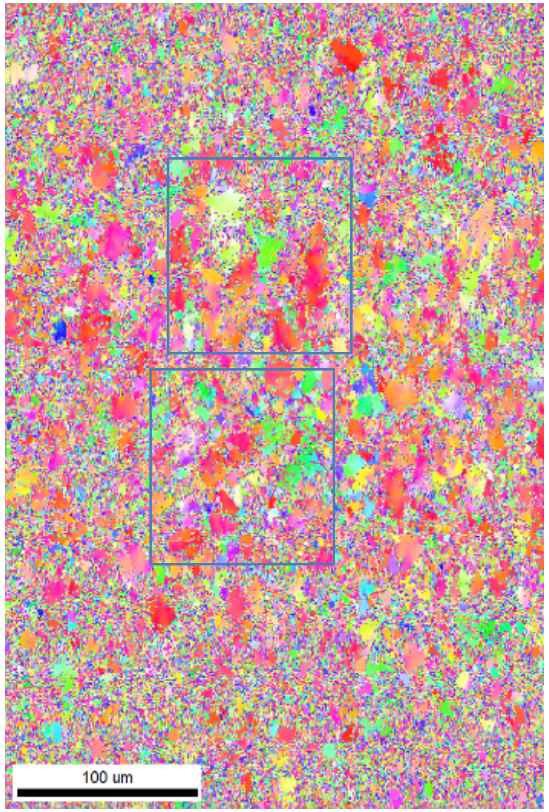
Observations

- Deterioration of the quality of the EBSD scan after irradiation.

Ti-6Al-4V

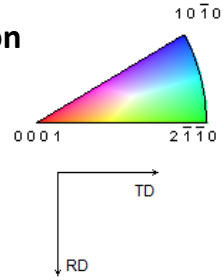


IPF map before irradiation

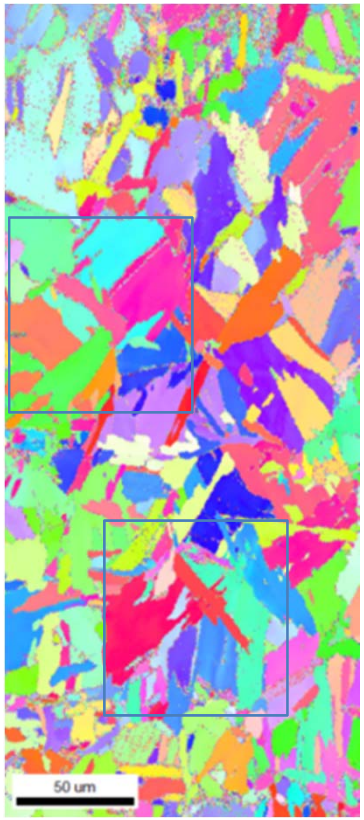


IPF map after irradiation

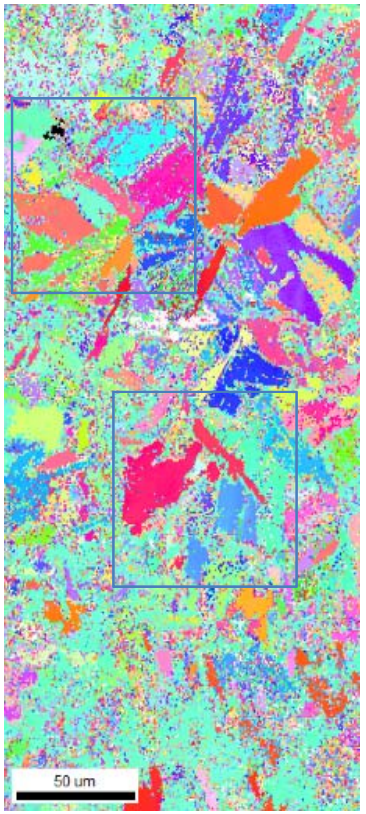
Ti-6Al-4V Irradiated at NSCL: Ca@2000MeV
T=20°C and a fluence of 6.10^{12}Ions.cm^{-2} and dpa at the surface of 10^{-5}dpa



Ti-6Al-4V-1B



IPF map before irradiation



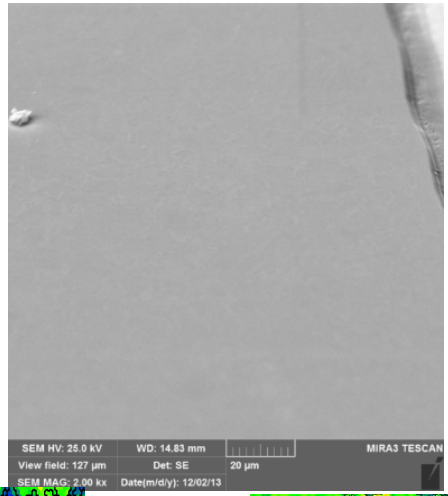
IPF map after irradiation

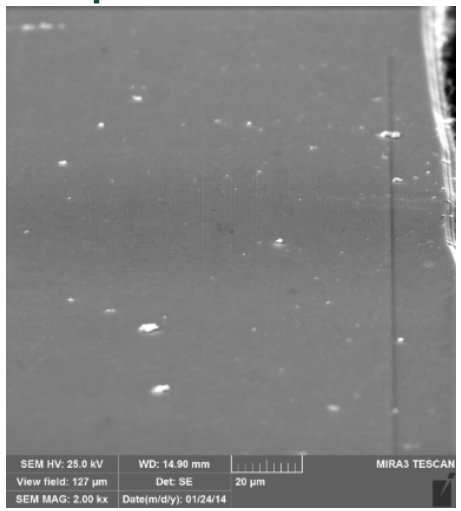
Ti-6Al-4V-1B Irradiated at CIMAP: Ar@36MeV
T=350°C and a fluence of 10^{15} Ions/cm and dpa at the surface of 0.038dpa

SEM and EBSD characterization of the surface of the samples:

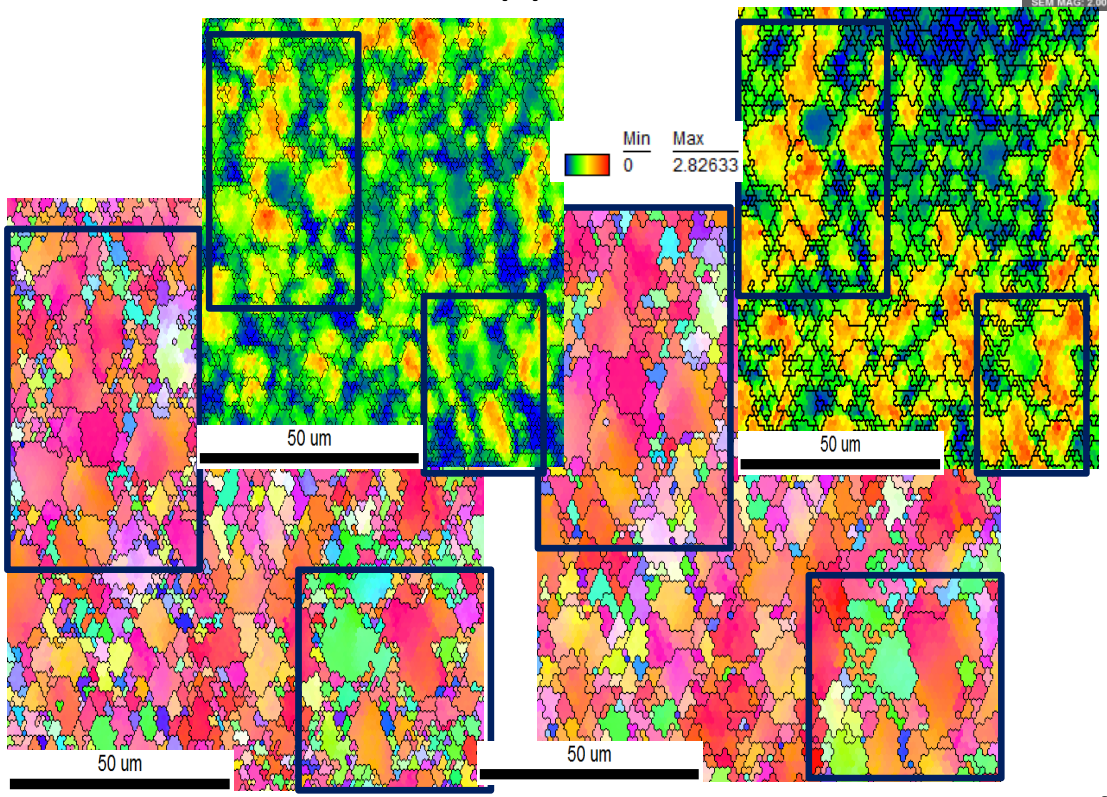
No change in the microstructure or the orientation of the grains at the surface.

Irradiated at CIMAP: Ar@36MeV
T= 350 °C
Fluence = 10^{15} ions.cm^{-2}
Dose at the surface= 0.038dpa

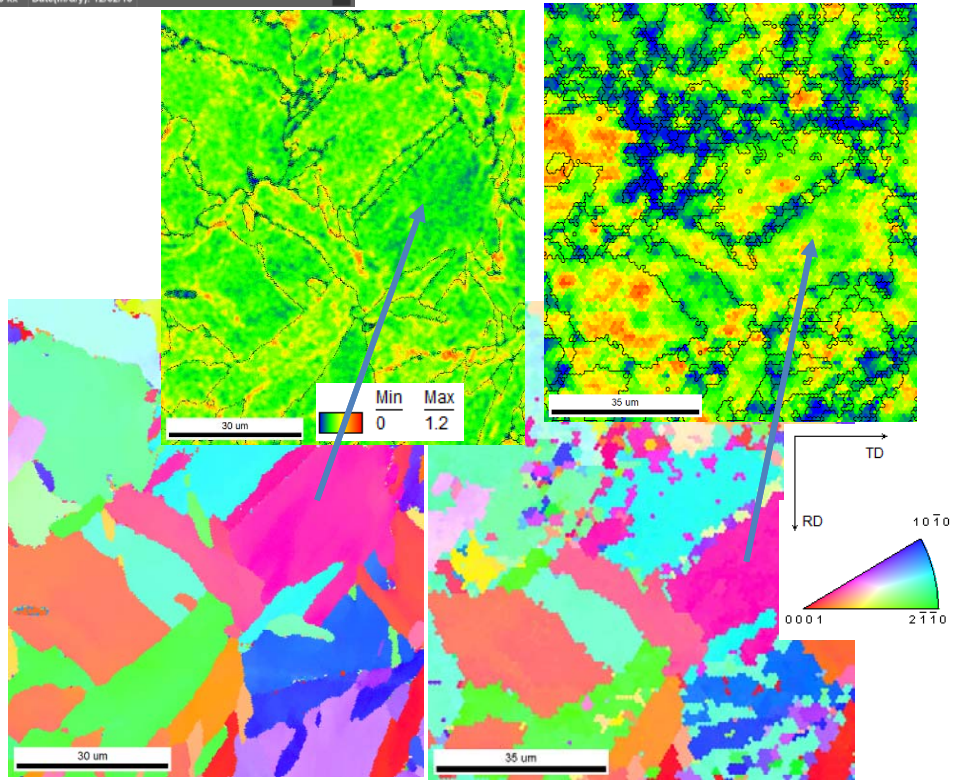




SEM image of the EBSD area before (a) and after (b) irradiation for Ti-6Al-4V



IPF and local average misorientation maps the grains before and after irradiation of Ti-6Al-4V



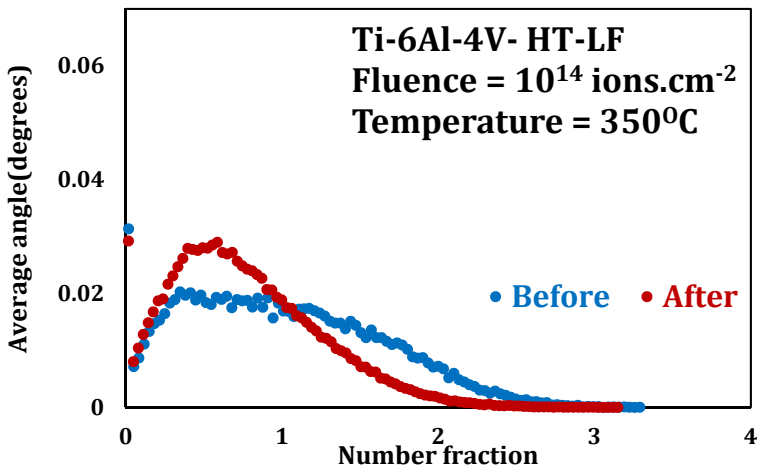
IPF and local average misorientation maps the grains before and after irradiation of Ti-6Al-4V-1B

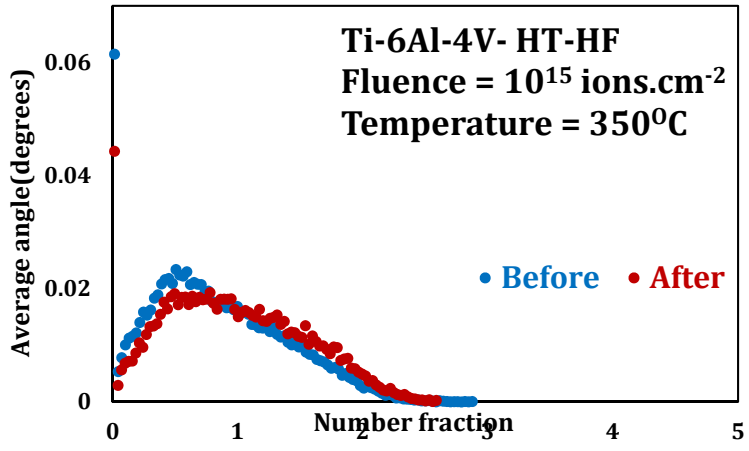
Local Average misorientation charts

Low energy irradiation: Ar36@36MeV

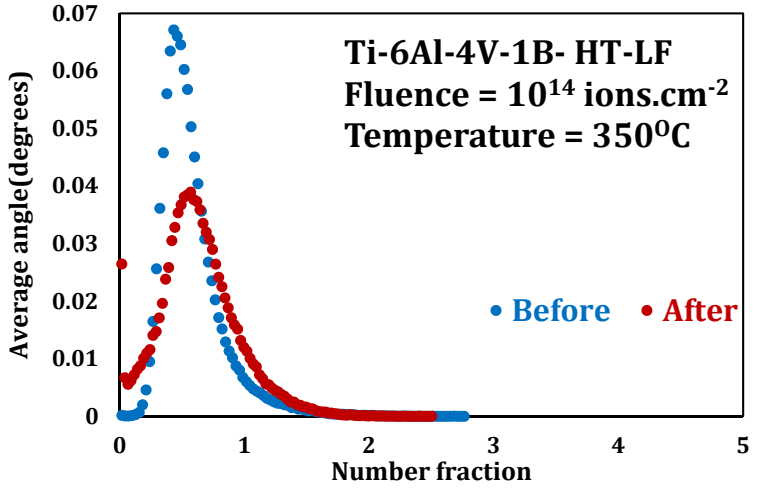
Comparison between Ti-6Al-4V and Ti-6Al-4V-1B only alpha phase

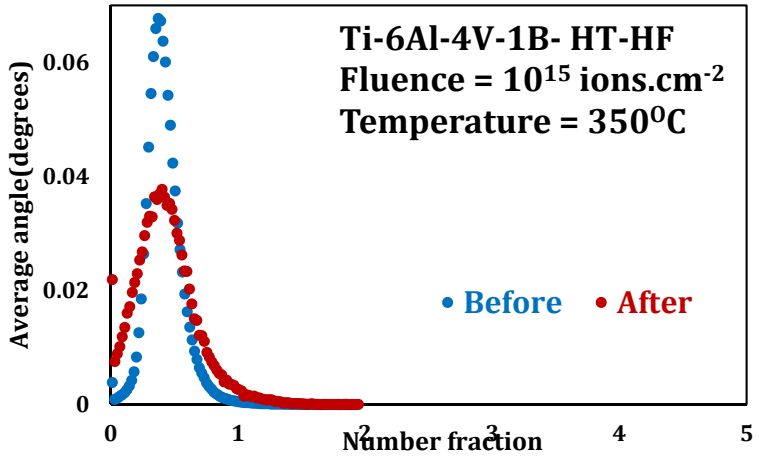
Ti-6Al-4V





Ti-6Al-4V-1B

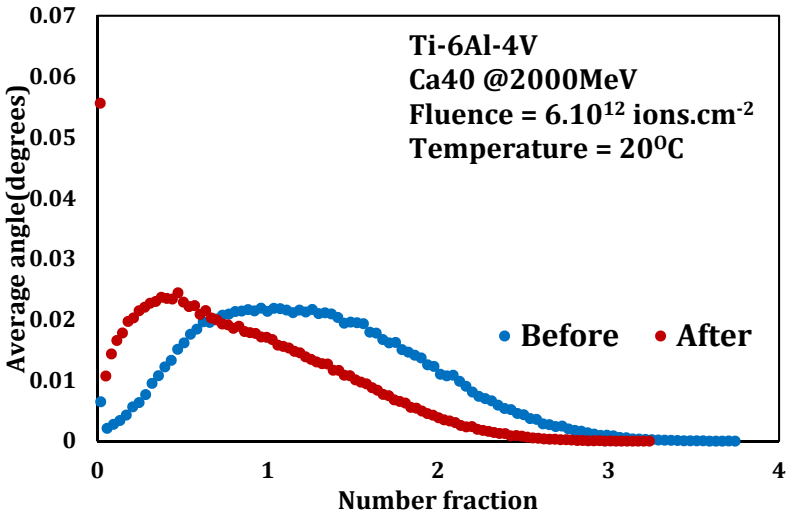


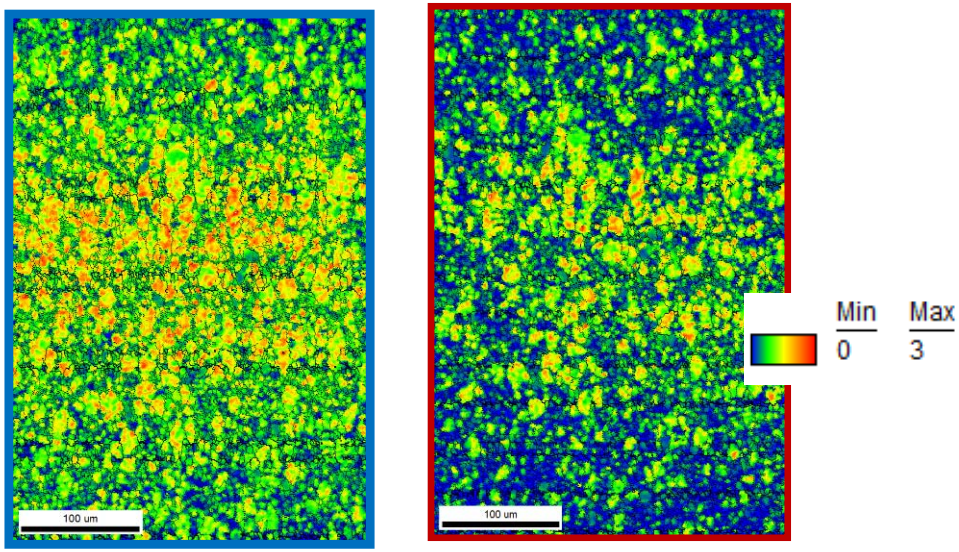


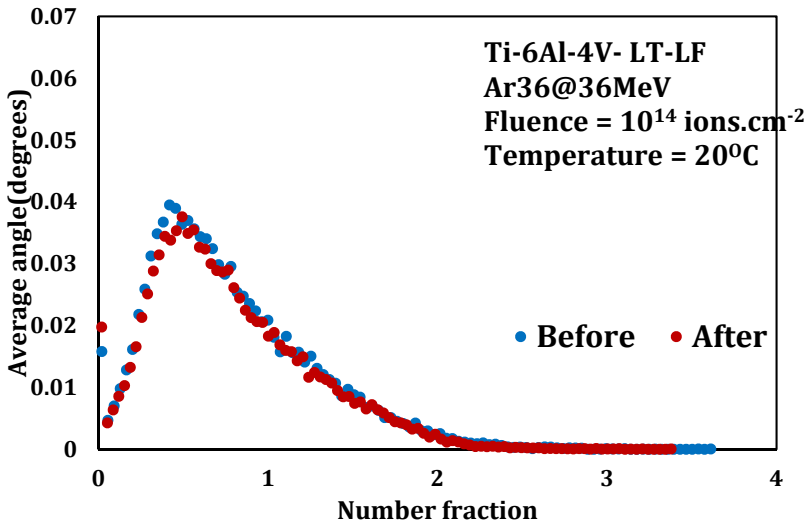
Unexpected changes in the local average misorientation for Ti-6Al-4V-1B

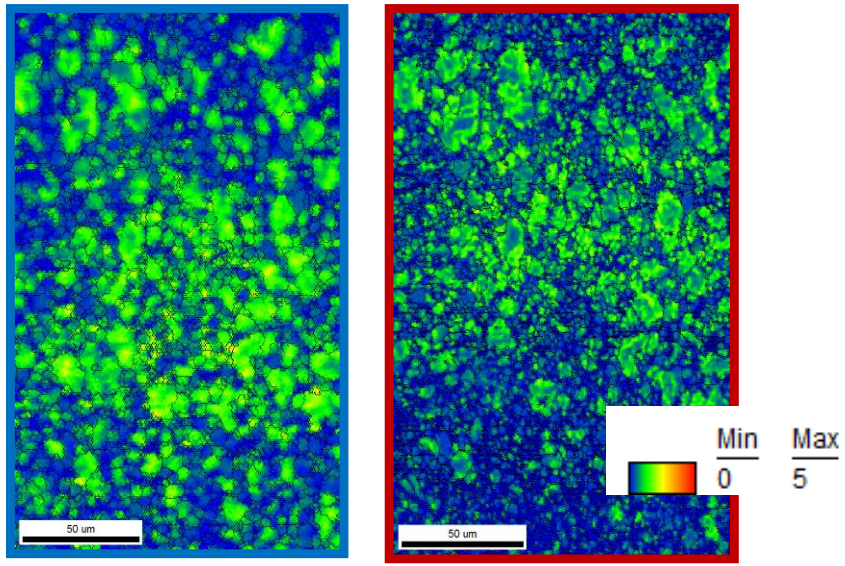
Local Average misorientation charts

Comparison between high energy and low energy irradiation









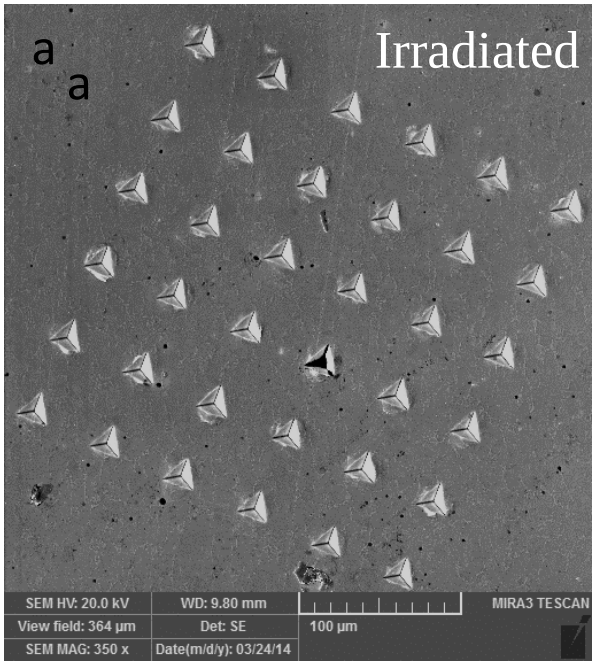
At high energy irradiation, the local average misorientation are more affected in Ti-6Al-4V

Mechanical testing: Nano-indentation

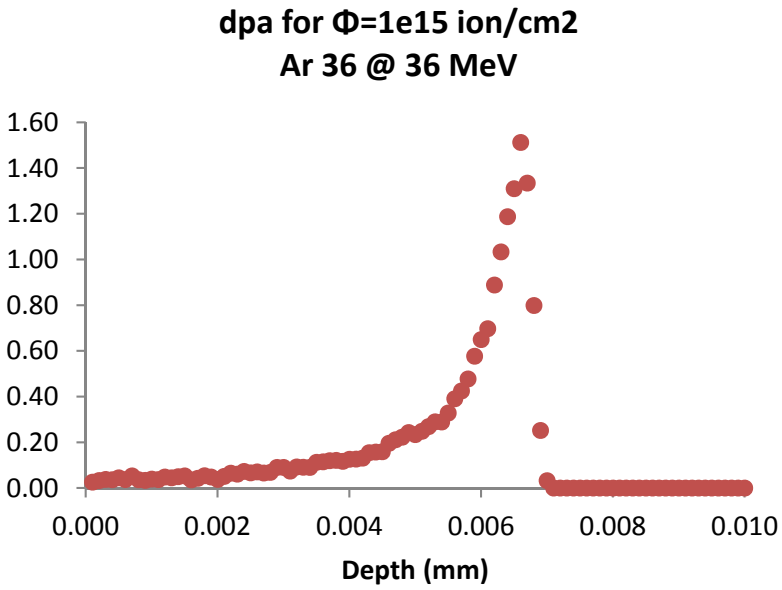
Obtain the properties of the materials in depth.

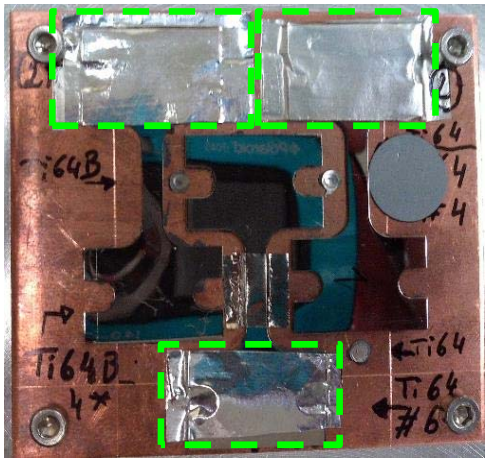
Parameters:

- Berkovich tip
- Strain rate : $0.05s^{-1}$
- Poisson ratio=0.33
- Distance between indents: 50µm



SEM image of nanoindents matrix in Ti-6Al-4V irradiated at T= 20 °C and a fluence of 10^{15} ions.cm^{-2}

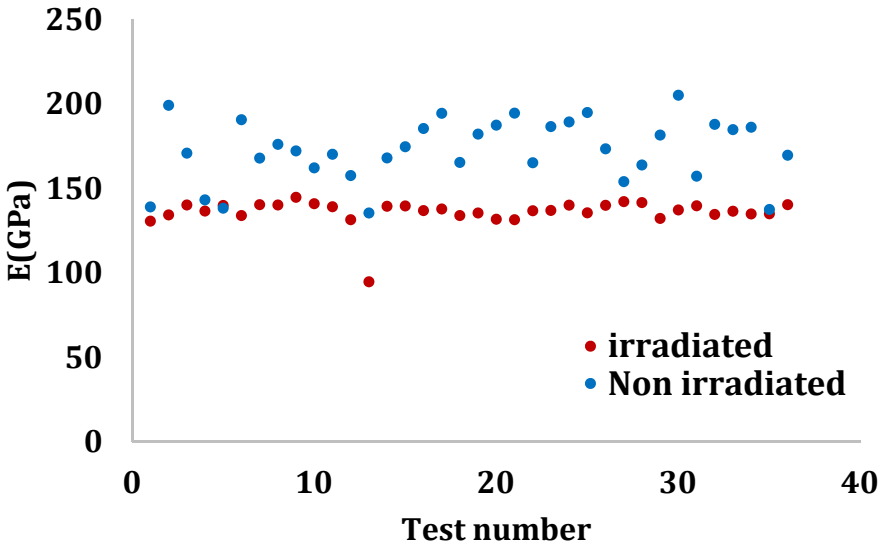


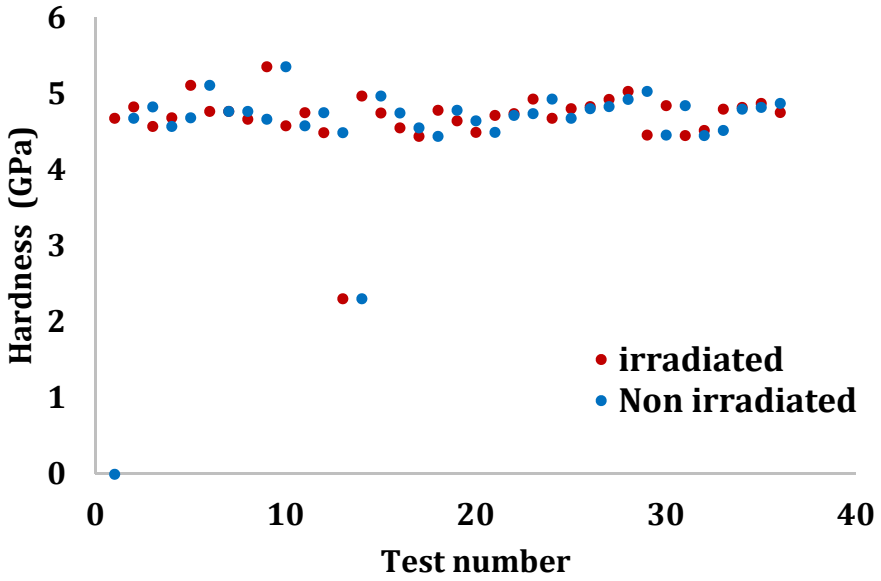


In all samples one grip was masque in order to compare irradiated to not irradiated properties in the same sample

Nano-indentation results

Ti-6Al-4V
Ar36 @36MeV
T= 20 °C
Fluence = 10^{15} Ions.cm^{-2}
Dose= 0.038dpa



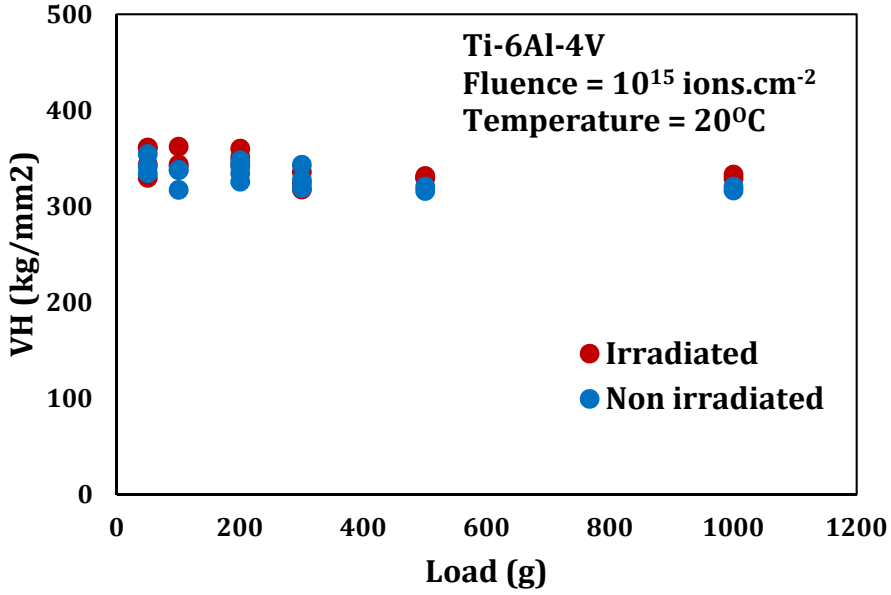


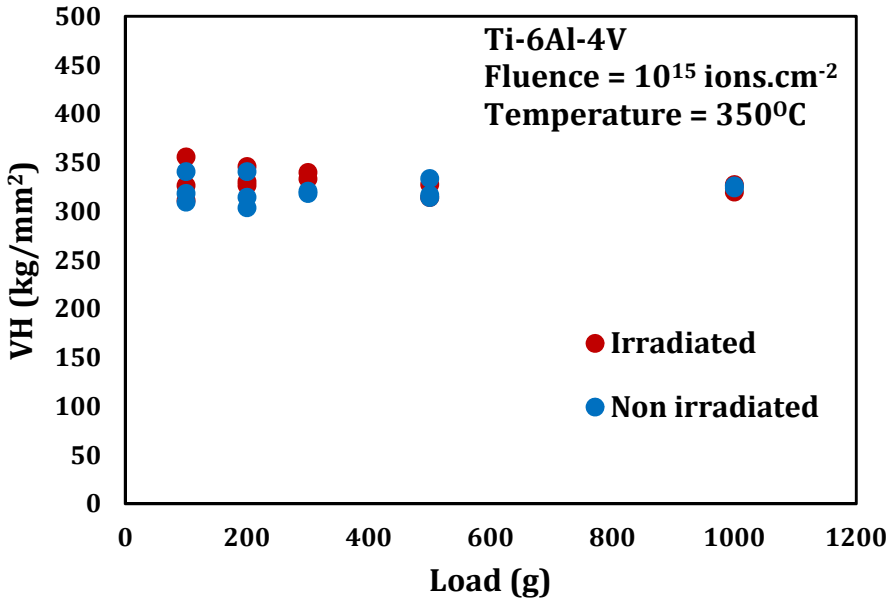
No change in hardness was observed
Decrease in the elastic modulus after irradiation

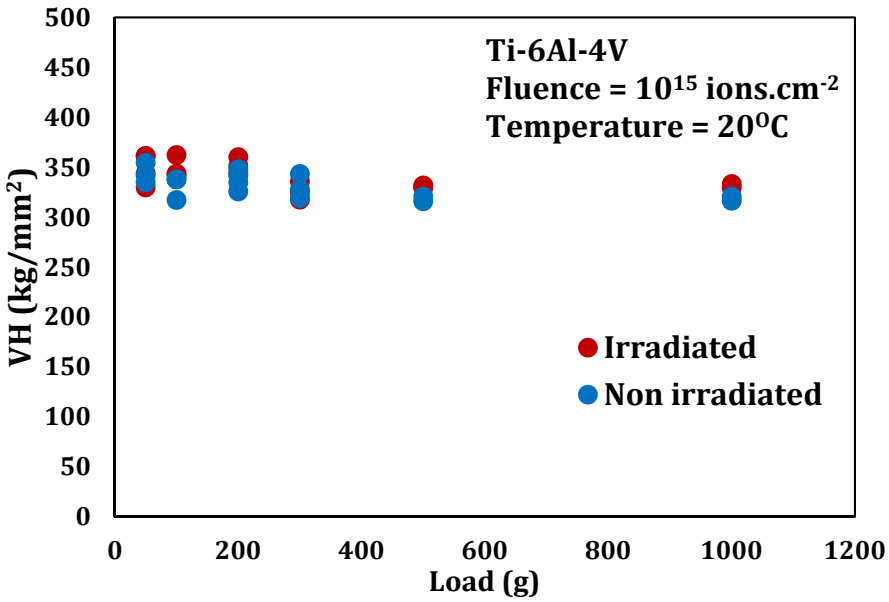
Vickers Hardness tests:

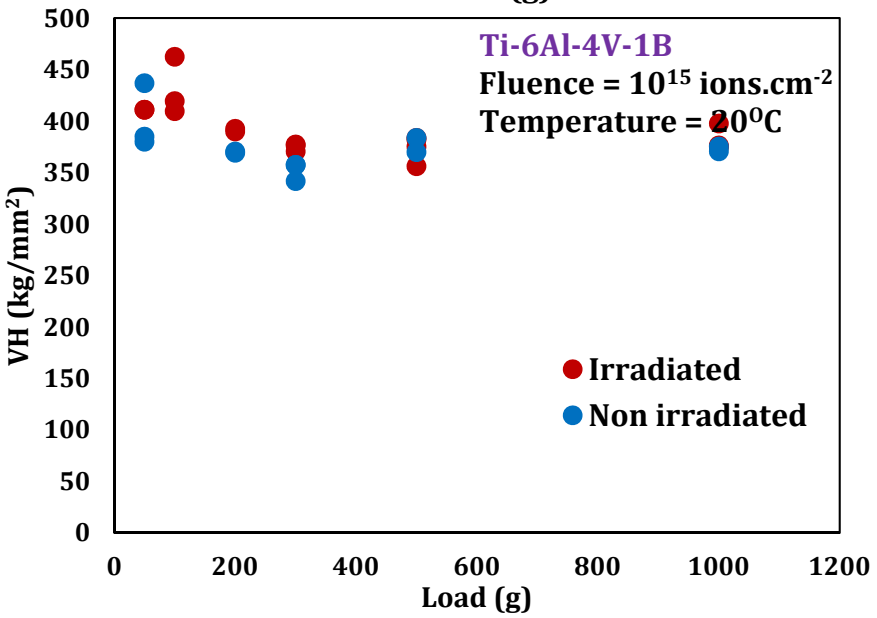
Ar @36 MeV

No change in hardness



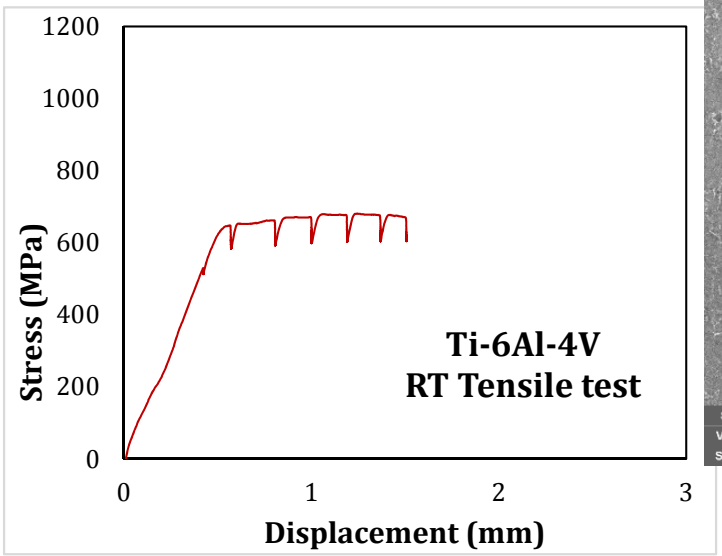


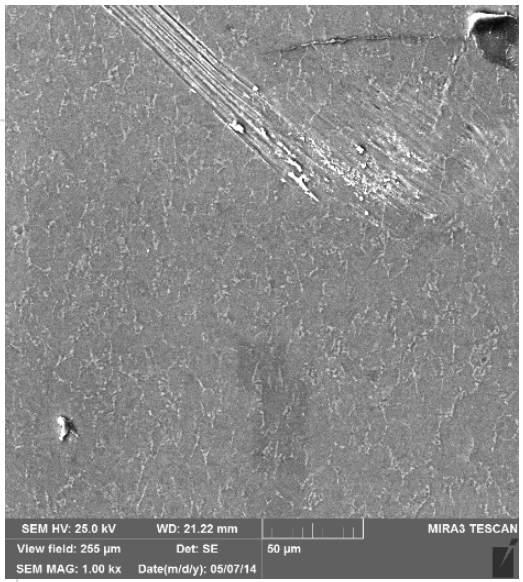


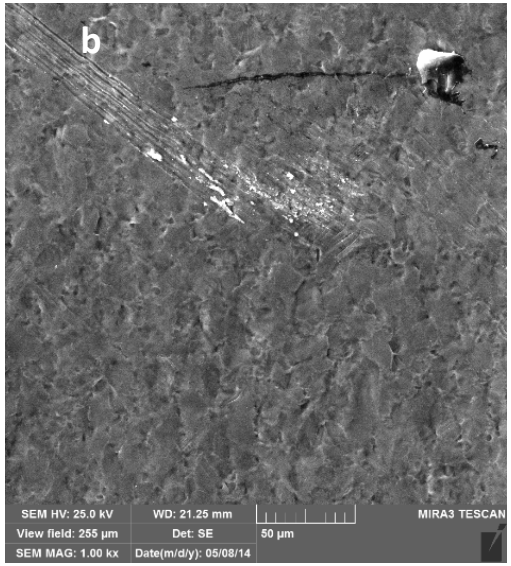


In-situ Tensile tests: Preliminary results

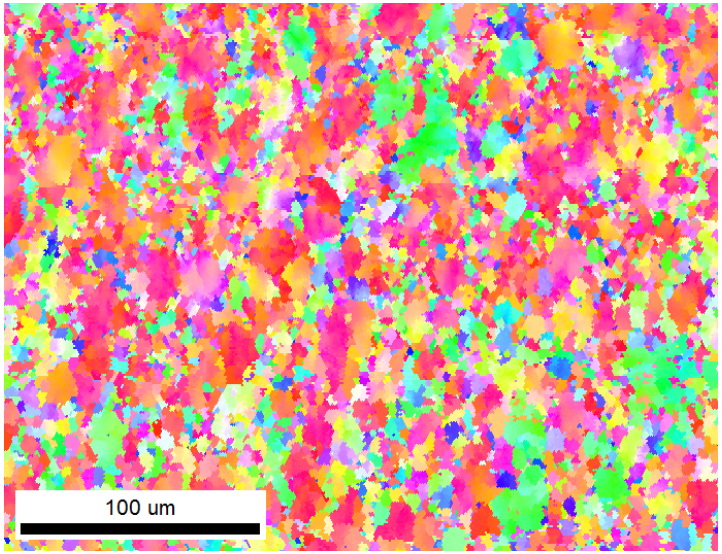
Ion beam : Ca 40 @2000MeV
T= 20°C
Fluence = 6.10^{12} ions.cm^{-2}
Max dpa= 10^{-5} dpa



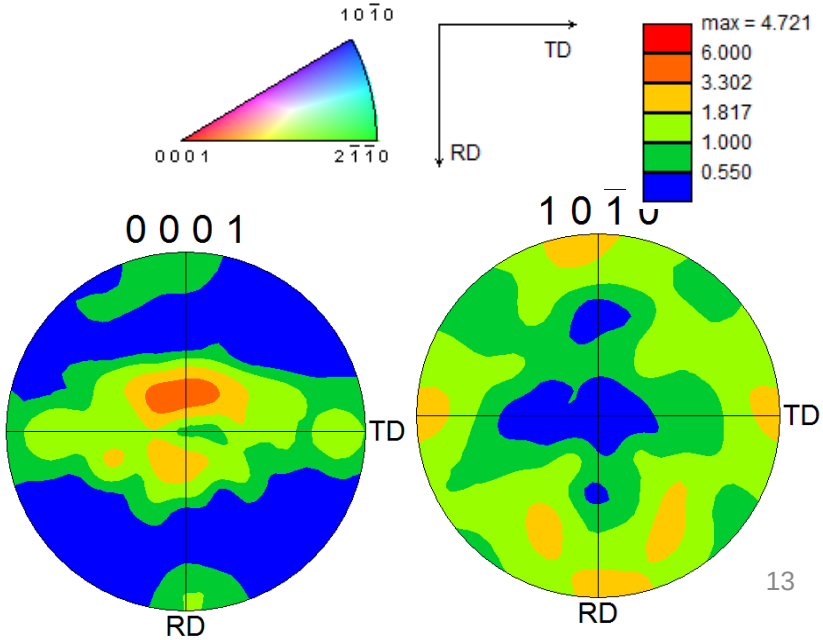




SEM images of the same area (a) before the tensile test and (b) at 13% strain

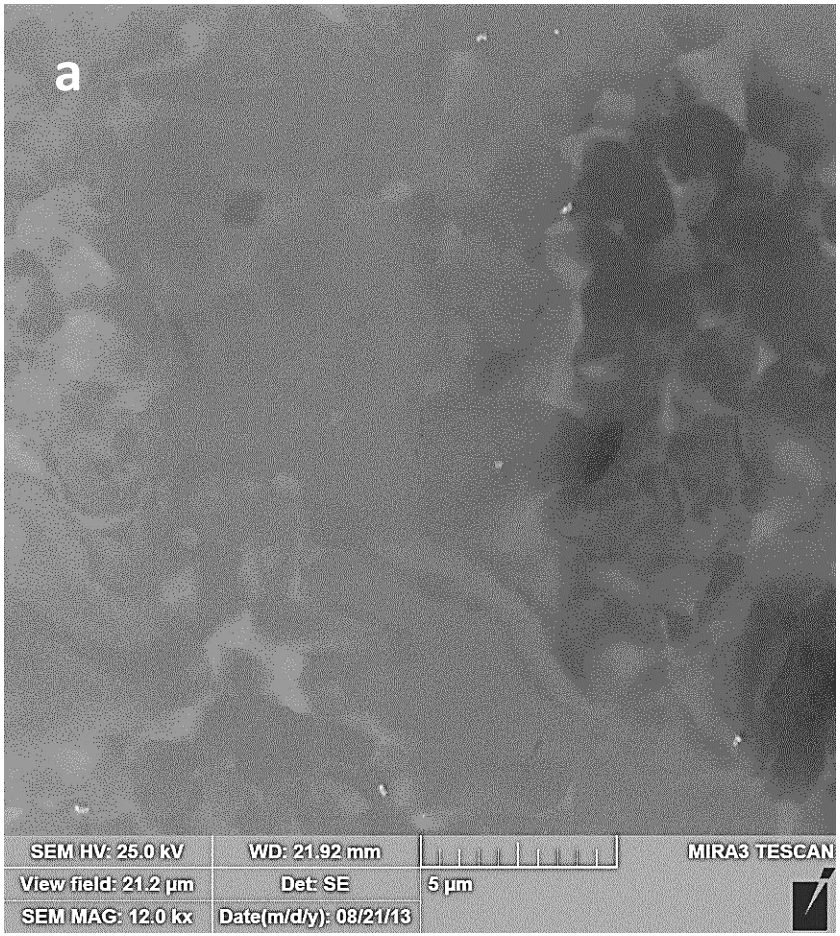


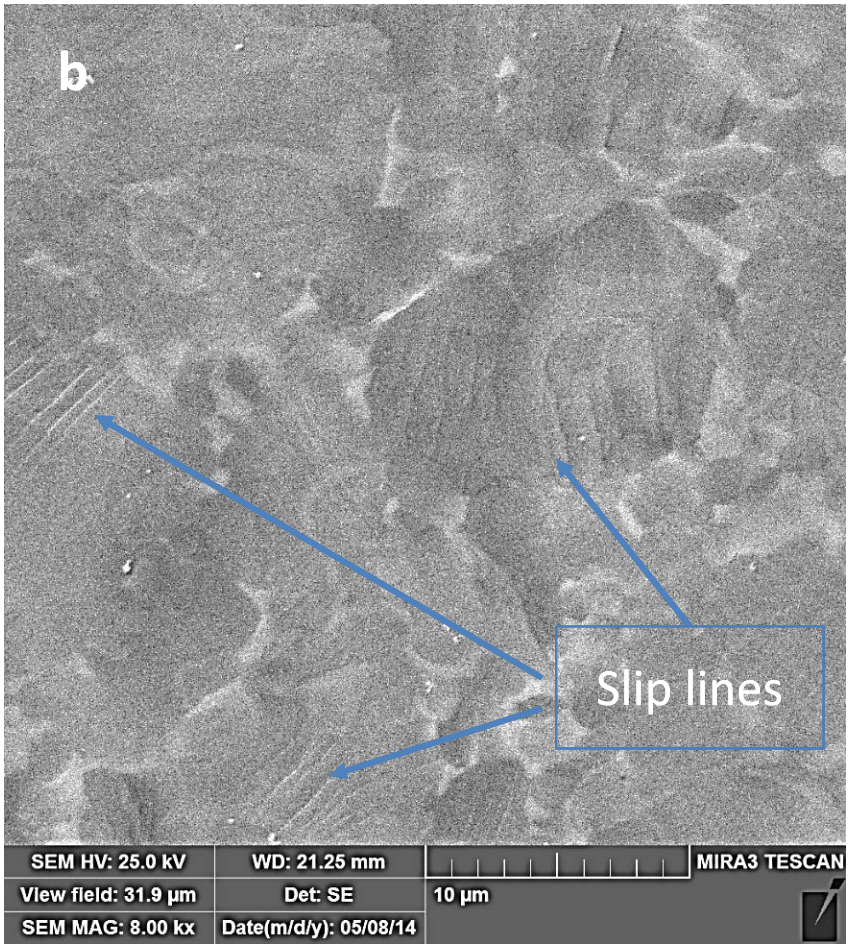
IPF map , {0001} and {10-10} pole figures of the α phase in the same area before irradiation



Evolution of the microstructure during the test

Ion beam : Ca 40 @2000MeV
T= 20°C
Fluence = 6.10^{12} ions.cm^{-2}
Max dpa= 10^{-5} dpa

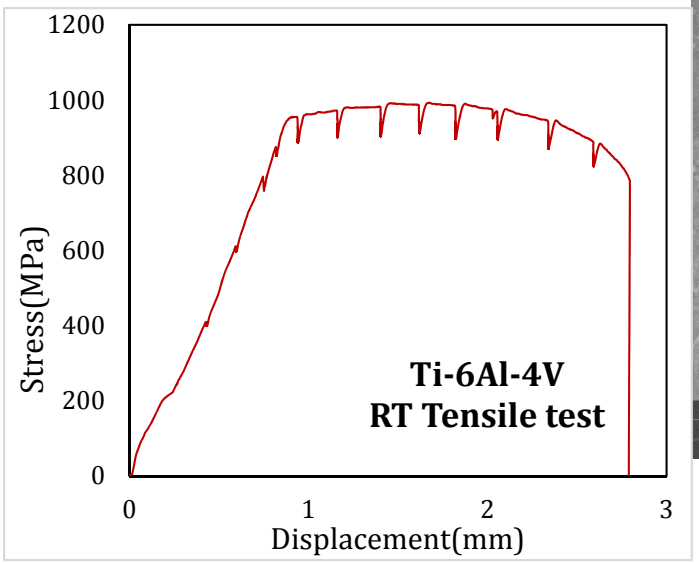


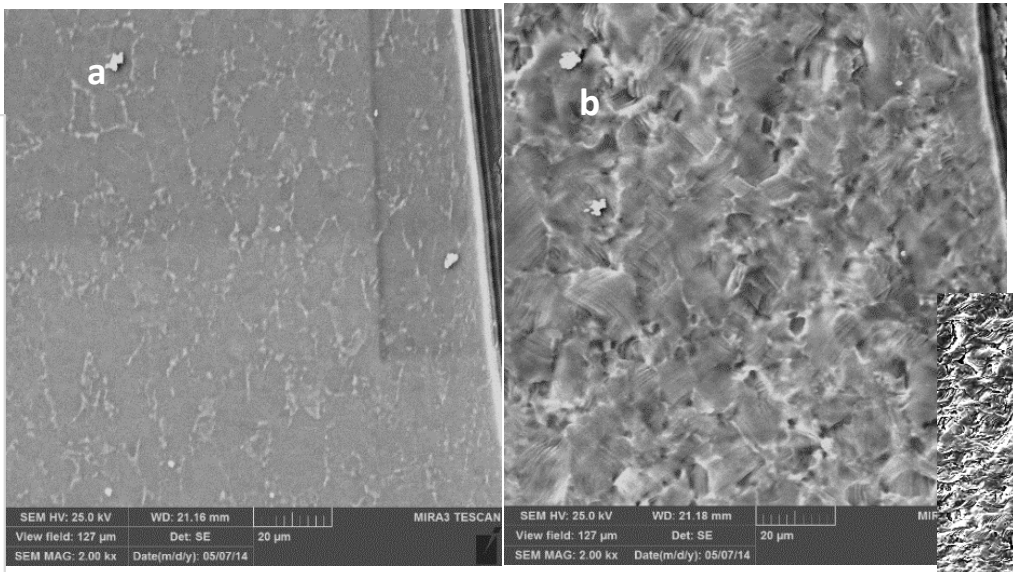


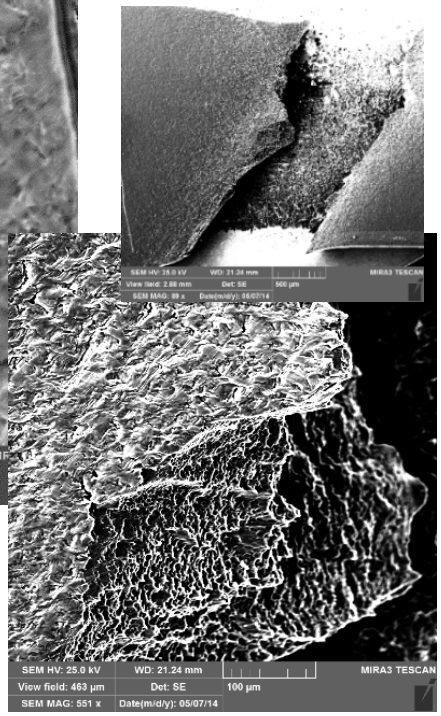
Microstructure of irradiated Ti-6Al-4V (a) before the tensile test and (b) at 5.27% strain

In-situ Tensile tests: Preliminary results

Ion beam : Ar@36MeV
T= 350 °C
Fluence = 10^{15} ions.cm^{-2}
Max dpa= 1.5 dpa

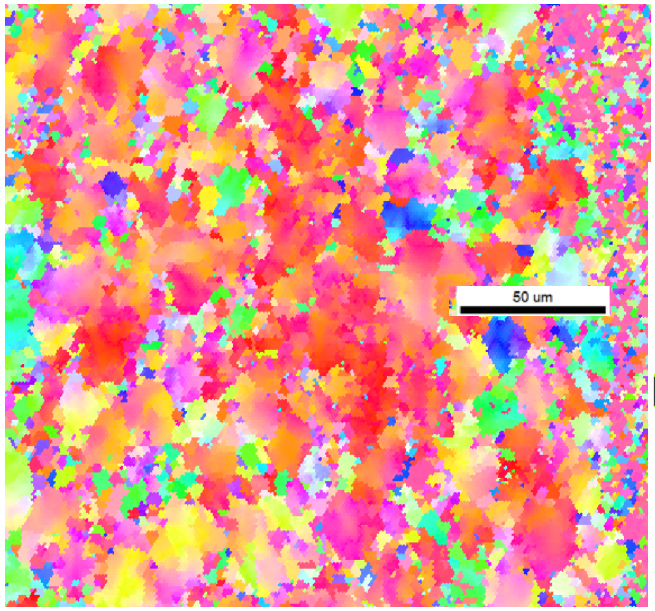


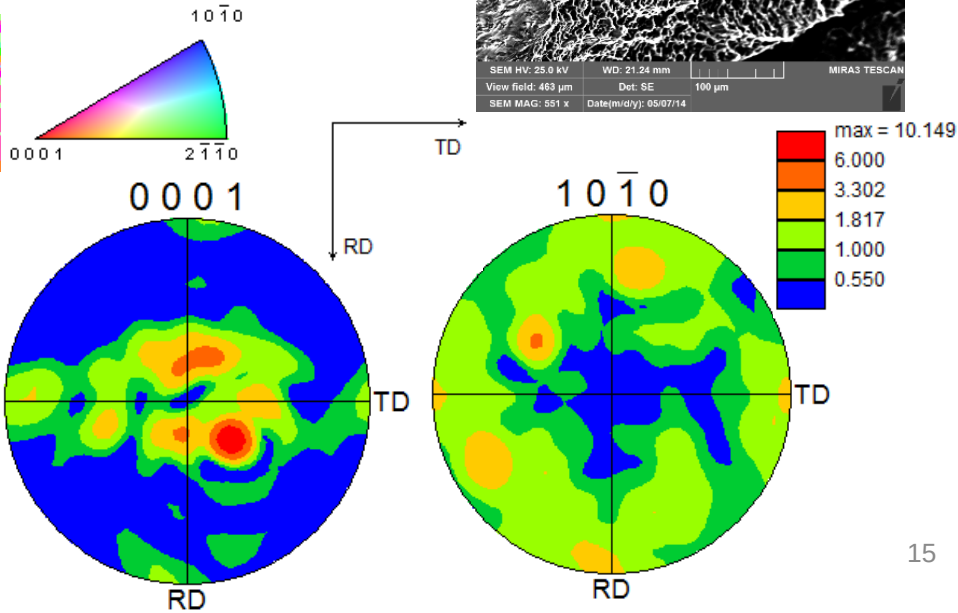




SEM images of the same area (a) before the tensile test (b) at 18.7 % strain, (c) failure surface

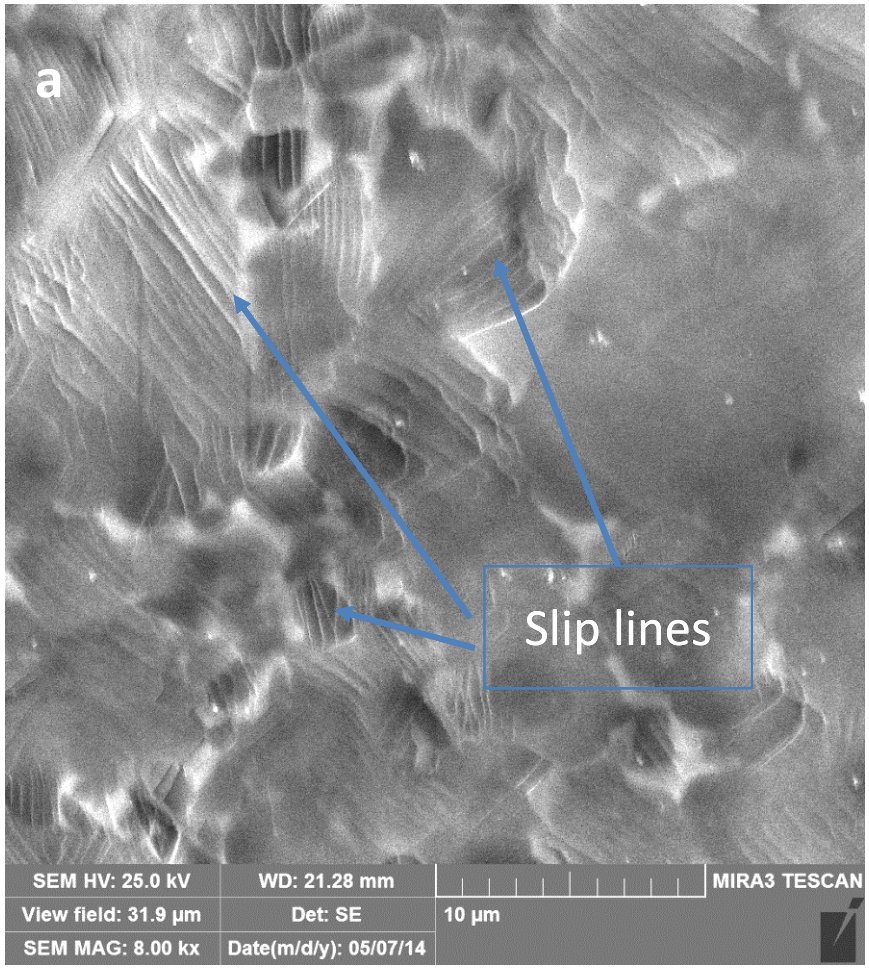
IPF map , {0001} and {10-10} pole figures of the α phase in the same area before irradiation

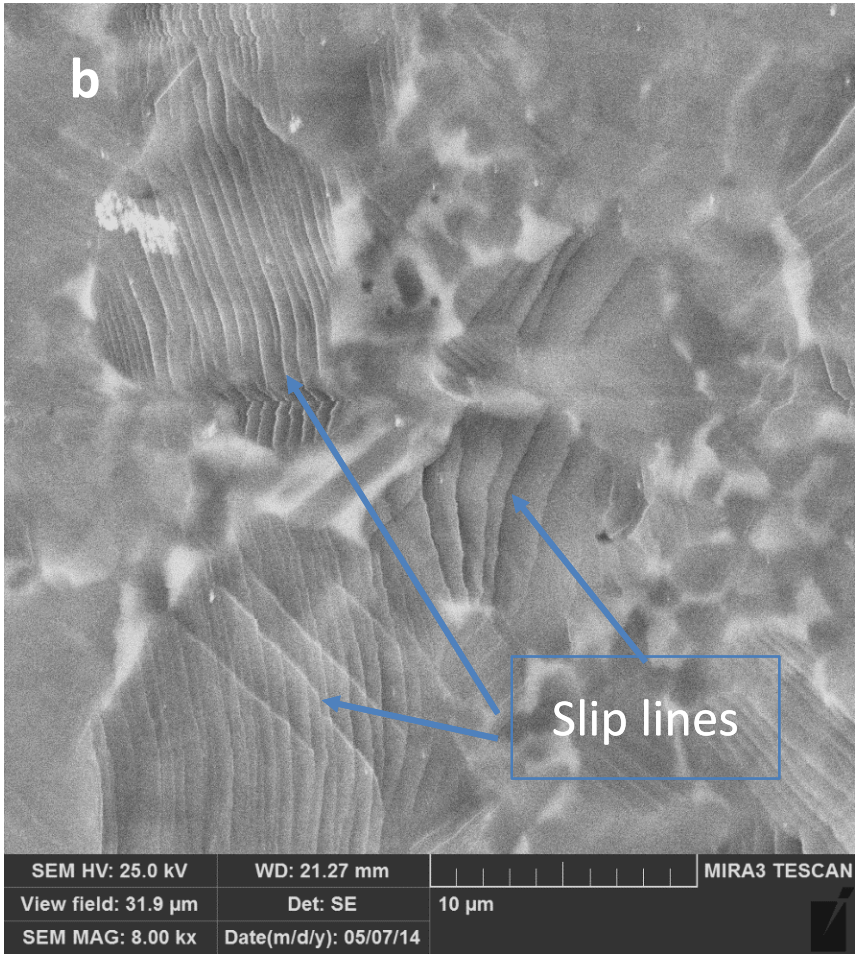




Evolution of the microstructure during the test

Ion beam : Ar@36MeV
T= 350 °C
Fluence = 10^{15} ions.cm^{-2}
Max dpa= 1.5 dpa

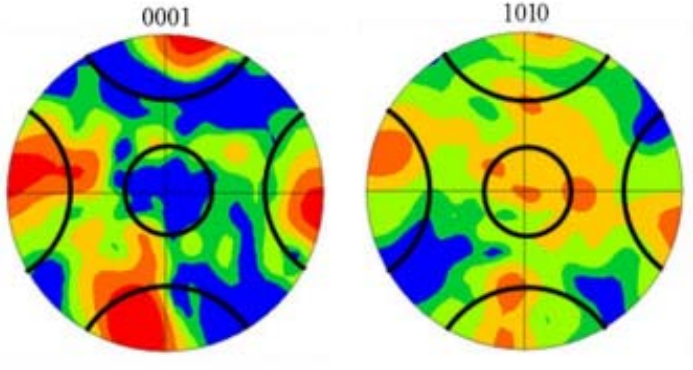




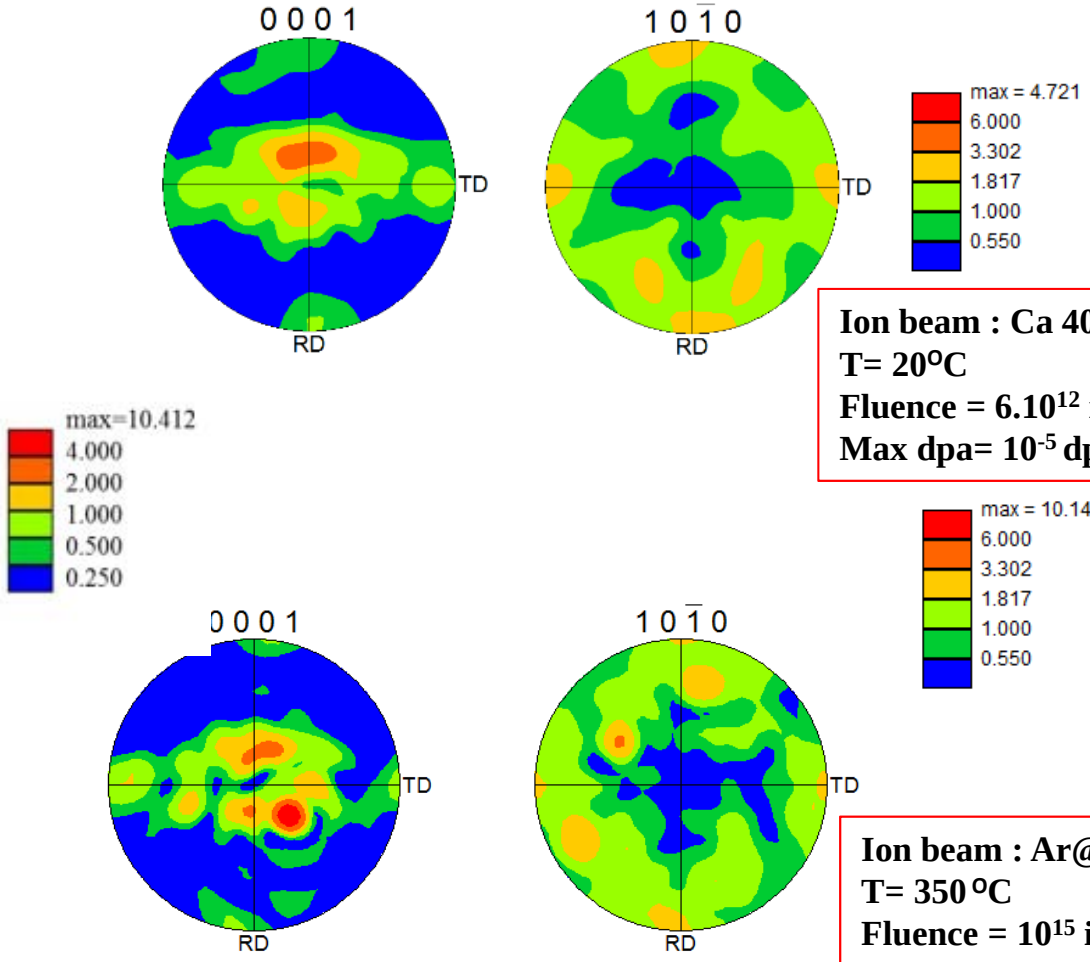
Microstructure of irradiated Ti-6Al-4V (a) at 6.77% strain and (b) at 9.38% strain

In-situ Tensile tests: Preliminary results

Texture of the tested Ti-6Al-4V



Non-irradiated Ti6Al-4V sample [Li.]

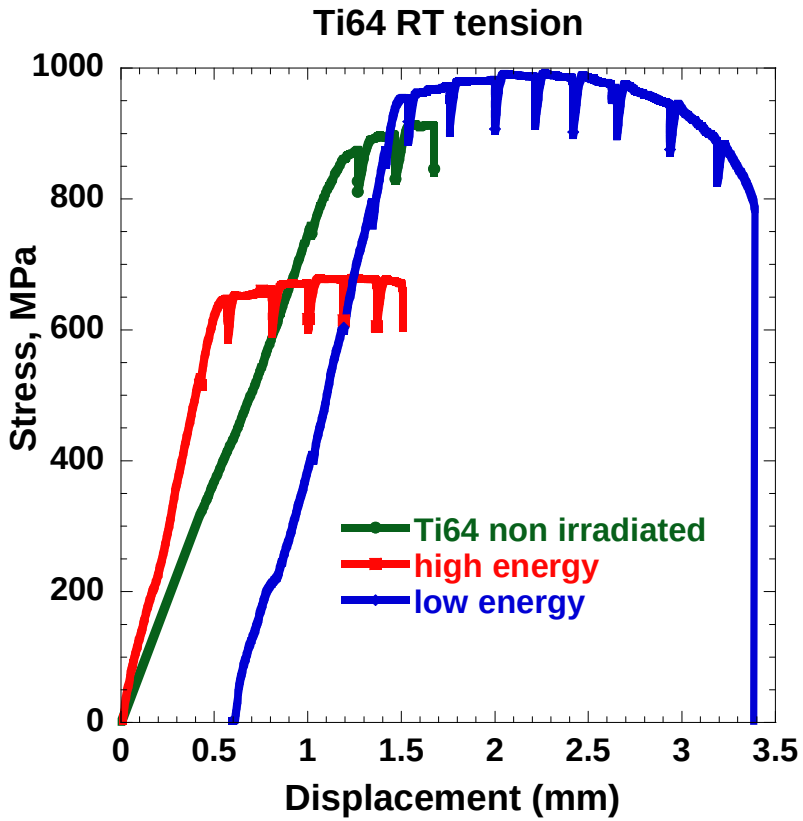


Ion beam : Ca 40 @2000MeV
T= 20°C
Fluence = 6.10^{12} ions.cm^{-2}
Max dpa= 10^{-5} dpa

Ion beam : Ar@36MeV
T= 350 °C
Fluence = 10^{15} ions.cm^{-2}
Max dpa= 1.5 dpa

Hongmei L,"ANALYSIS OF THE DEFORMATION BEHAVIOR OF THE HEXAGONAL CLOSE-PACKED ALPHA PHASE IN TITANIUM AND TITANIUM ALLOYS", PhD disseretation , Michigan State University

In-situ Tensile tests: Comparison with other Ti64 RT tension Test



For low energy irradiation no change in the mechanical properties (the damage is only on the surface (7 microns).

For high energy irradiation, even at low doses, we observed a significant decrease in the UTS.

More tests are required

Conclusion

- Ongoing analyses:
  - Nano-indentation tests on the cross sections of the samples will allow extraction of hardness and Young modulus for different dpa doses.
  - In-situ tensile tests: Comparison between non irradiated and irradiated Ti-alloys and slip trace analysis
- Future analyses
  - New EBSD analyses planned after electro-polishing the samples
  - Swelling measurements on each samples
  - Possibility to use FIB (Focused Ion Beams) to study the damage in the depth of the sample for TEM, SEM/EBSD analyses
  - In-situ irradiation and creep test