Heavy ion radiation damage in commercially pure Titanium and Ti-6Al-4V: Characterization of the microstructure and mechanical properties

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Introduction

Due to their high specific strength, good fatigue and creep properties, corrosion resistance, as well as their commercial availability, titanium (Ti) alloys have been widely used in industrial, aerospace and biomedical applications. Ti-6Al-4V(wt.%) was selected to be a structural material for the beam dump for the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU). Through this study our goal is to investigate the change in microstructure and mechanical properties due to heavy ion radiation damage in Commercially pure (CP) CP-Ti and Ti-6Al-4V.

Experimental

The materials irradiated and characterized are: Commercially pure (CP) Ti and Ti-6Al-4V samples processed through two different thermomechanical processes: powder metallurgy (PM) rolled and additive manufacturing (AM). The latter was processed by direct metal laser sintered (DMLS) followed by hot isostatic pressing (HIP).

Ion beam	Temperature (°C)	Dose rate (dpa/h)	Energy (MeV)	Range (µm)	S_e (keV/nm)	Material
^{36}Ar	350	0.006	36	6.6	7.4	Ti-6Al-4V PM
^{36}Ar	25 , 350	0.17	0.78	0.5	1.4	Ti-6Al-4V PM
^{40}Ar	25	20.14 1.14	4	1.79	3.16	Ti-6Al-4V PM, Ti-6Al-4V AM, CP-Ti
^{40}Ar	350	21.8	4	1.79	3.16	Ti-6Al-4V PM, Ti-6Al-4V AM, CP-Ti

Figure 1. The different irradiation conditions of samples included in this study

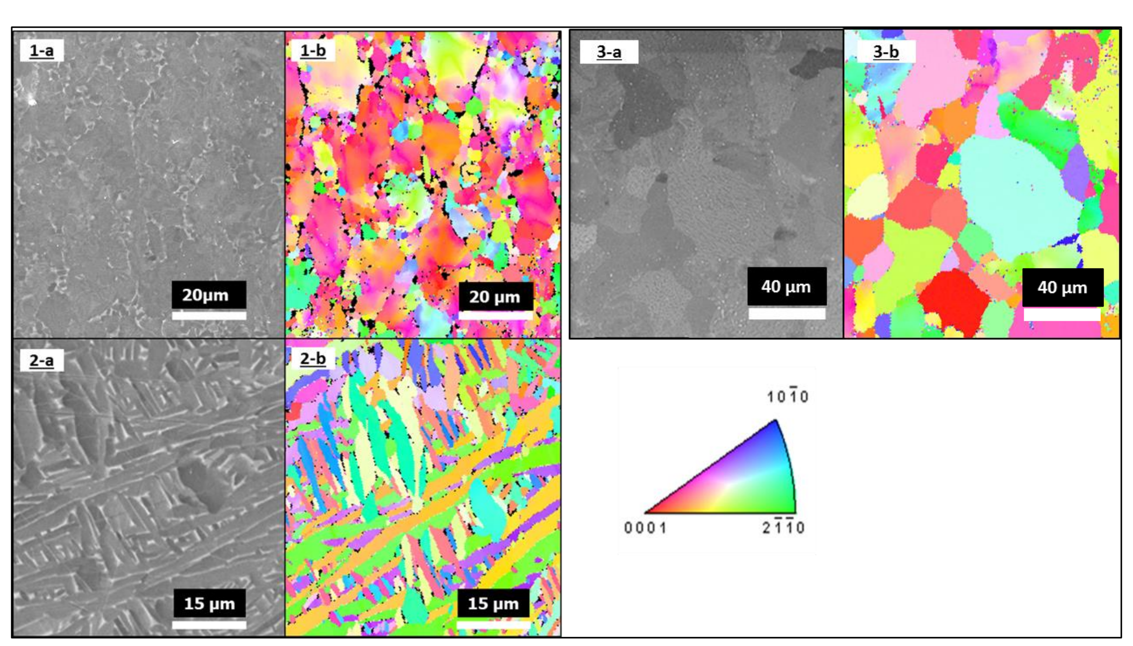


Figure 2. a- BSE and b- EBSD inverse pole figures illustrating representative microstructures of the studied as-processed materials:1- Ti-6Al-4V PM rolled and 2 - Ti-6Al-4V additively-manufactured and 3- Commercially pure Ti

Nano-indentation results

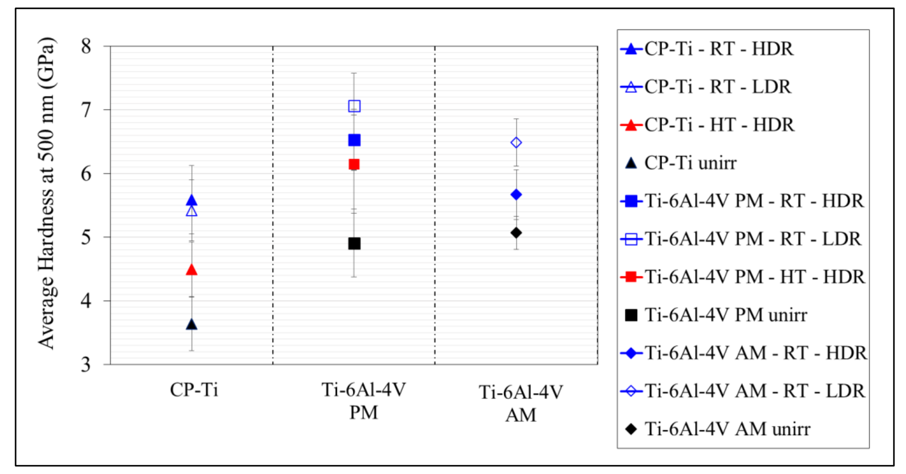


Figure 3. Average hardness values at ~ 500nm for samples irradiated with 4 MeV Ar ions: Blue symbols represent RT irradiated samples, red symbols represent samples irradiated at 350°C (HT) while the black symbols represent the un-irradiated samples; the solid (filled-in) symbols represent the high dose rate (HDR) (~20 dpa/hr) condition, while the empty symbols represent the low dose rate (LDR) (~1 dpa/hr).

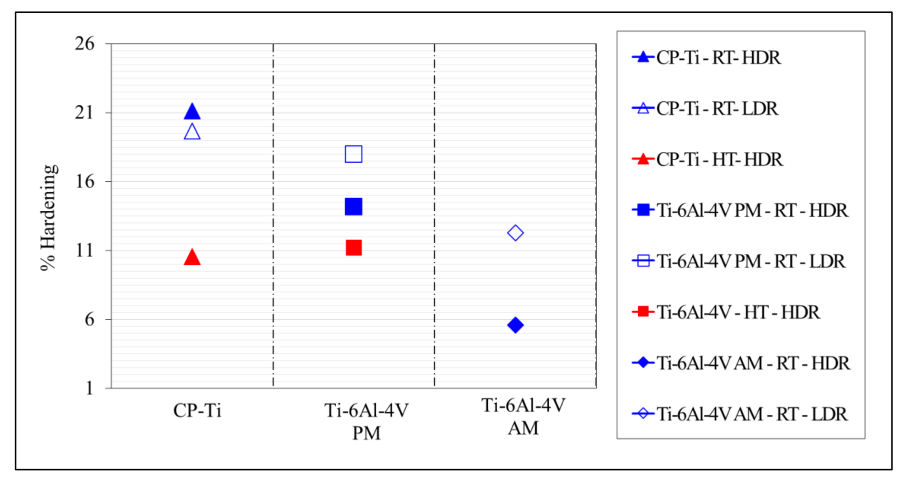


Figure 4. % Hardening for samples irradiated with 4 MeV Ar ions: Blue symbols represent RT irradiated samples, red symbols represent samples irradiated at 350°C (HT) while black symbols represent the un-irradiated samples and; the solid (filled-in) symbols represent the high dose rate (HDR) (~20 dpa/hr) condition, while the empty symbols represent the low dose rate (LDR) (~1 dpa/hr).

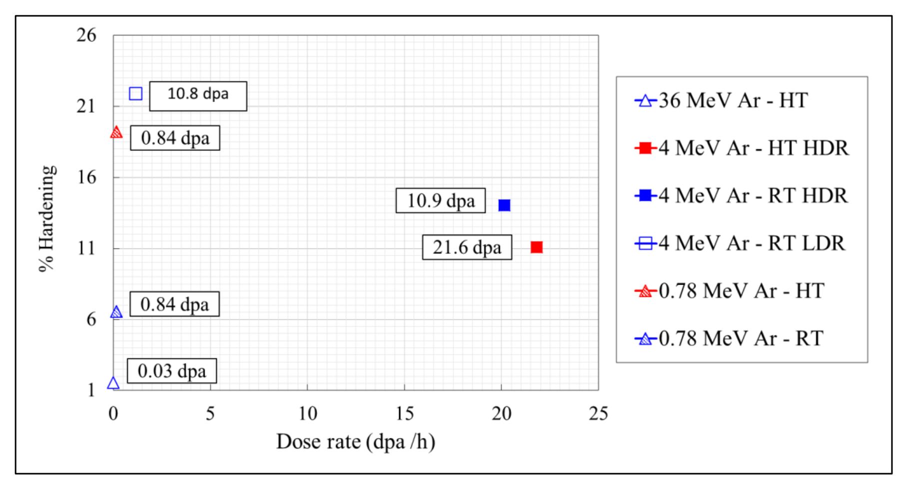
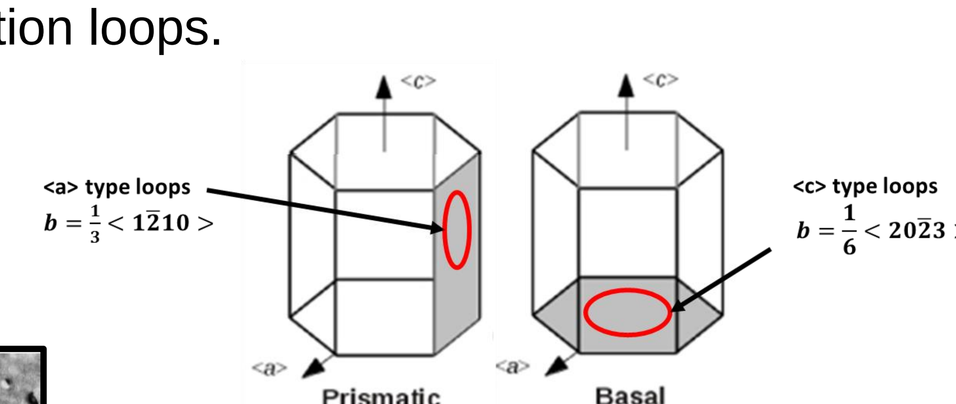


Figure 5. Comparison of the relative hardness of PM rolled Ti-6Al-4V samples irradiated with 4 MeV Ar ion beam at Notre Dame 5U accelerator with previously published results [1] for the same material irradiated with Ar 36 MeV and using a foil at the surface (0.78 MeV) at CIMAP France: Blue symbols represent RT irradiated samples and red symbols represent samples irradiated at 350°C.

TEM characterization:

The main radiation induced defects in Ti alloys are <a> type and <c> type dislocation loops in addition to irradiation induced precipitates. The focus of this study is the characterizing the dislocation loops.

Figure 6. Schematic representation of the habit nucleation planes for dislocation loops in hcp materials



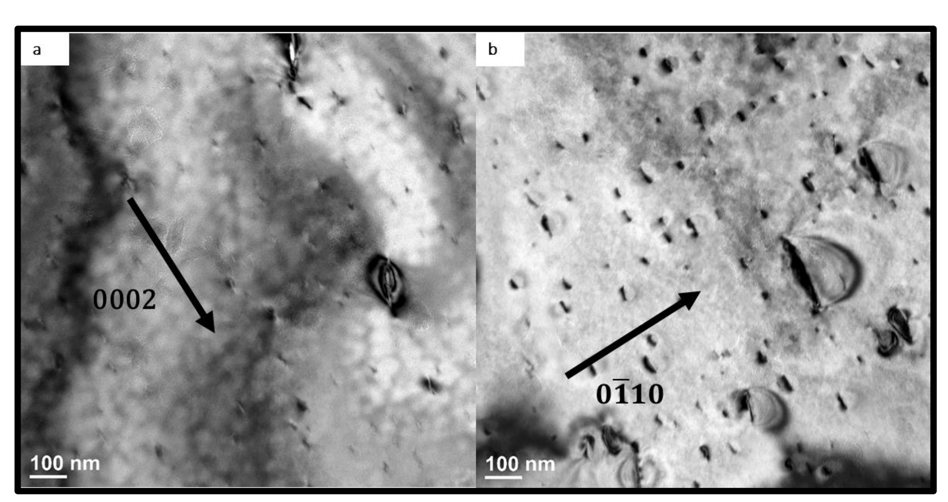


Figure 7. TEM BF micrographs of unirradiated CP-Ti sample a- Absence of <c> loops with a g=0002 and b- absence of <a> loop structure with g = $01\bar{1}0$

The nucleation and growth of these dislocation loops is dependent upon the irradiation temperature and dose. Figure 8 and 9 show the defects found in CP-Ti.

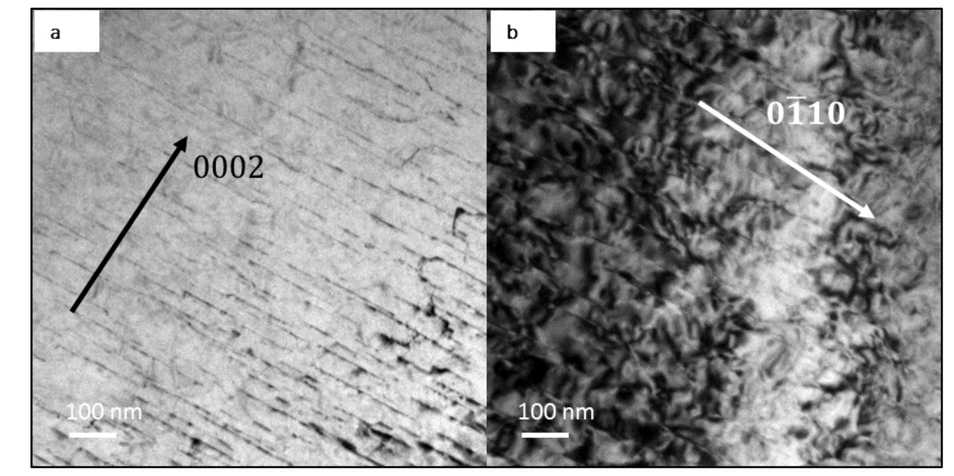


Figure 8. TEM bright field (BF) micrographs of the CP-Ti sample irradiated at 350°C with Ar ions at the dose rate of 9.7 dpa/hr: a- <c> loops imaged with g=0002 ; b- <a> loop structure imaged with g = $01\bar{1}0$

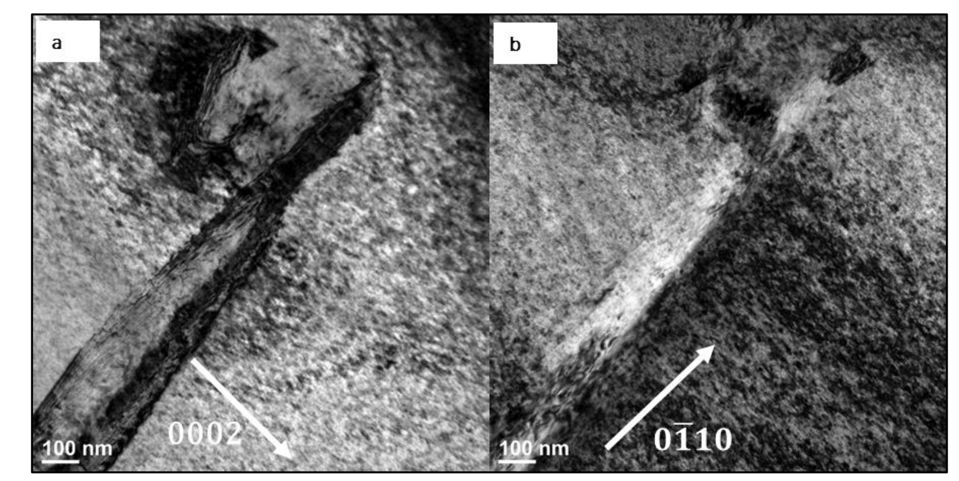


Figure 9. TEM BF micrographs of the CP-Ti sample irradiated at RT with with Ar ions at the dose rate of 9.7 dpa/hr: a- Absence of <c> loops with a g=0002 and b- <a> loop structure imaged with g = $01\bar{1}0$

Conclusions

- The comparison of the effect of the dose rate (DR) in RT irradiated samples showed that CP-Ti exhibited the highest irradiation induced hardening (~ 20%), whereas the nano-hardness of the additively manufactured Ti-6Al-4V was the most sensitive to the DR effect. The observed DR effect at low temperature for the Ti-alloys suggests the influence of irradiation enhanced precipitation even at such a low temperature [2,3].
- The influence of the temperature, dose and dose rate was investigated in PM rolled Ti-6Al-4V (Figure 5). At low doses, the contribution of temperature to the hardening (~ 13%) is higher than that of the dose. The low hardening (~11%) at 350°C at a high dose of 21.6% in our samples could be explained by a saturation of the <c> loop density (observed only in the α-phase grains in CP-Ti in Figure 8) as well as the precipitate density and size [2].
- Further investigation and transmission electron microscopy characterization is ongoing to better understand these different damage structures in the different irradiated Ti and Ti-alloy samples.

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