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DAMAGE BEHAVIOR OF TUNGSTEN TARGETS FOR 6 MeV LINEAR ACCELERATORS *

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Abstract

The target in electron linear accelerator is subjected to high-frequency and intense thermal shocks. Elevated temperatures in the target may lead to target recrystallization, fatigue cracking, creep and vaporization. In this study, experiments were carried out to investigate the damage behaviour of tungsten targets in 6 MeV linear accelerators under pulsed electron beam. The results show that recrystallization occurs after loading 6 MeV electron beam with repetition frequency of 220 Hz, pulse width of 4 μs and mean current of 151 μA for 248 s. Deformation and cracking caused by recrystallization are observed on the surface of the target.

INTRODUCTION

Medical linear accelerators are the most commonly used device for external beam radiation treatments for patients with cancer [1]. The X-ray target is a very important component at the end of the accelerating tube to produce high-energy X-ray. Pulsed electron beam deposits large amounts of heat within the target. The target exposed to high-frequency thermal shocks is at risks of damage, limiting the accelerator's ability to deliver high-dose-rate X-ray irradiation. Literature review shows several possible damage forms of the most commonly used tungsten targets [2-5]:

(1) Recrystallization. Recrystallization temperature of pure tungsten is reported to be 1300-1500 °C. After recrystallization, the crystal structures of tungsten atoms change, causing the changes in the macro-properties. Micro-cracks initiate and propagate along grain boundaries. Besides, embrittlement happens with the ductile brittle transition temperature (DBTT) rising from 70 °C to 230-280 °C.

(2) Fatigue cracking. Pulsed electron beam causes high-frequency thermal shocks on the target. Cyclic temperature variations lead to alternating stress and further mechanical fatigue of the target. As the temperature cycles cross the DDTT frequently, tungsten target shifts between flexible and brittle, easily initiating cracking and even failing.

(3) Melting and vaporization. The melting point of tungsten is 3410 °C. Melting occurs when the energy deposited on the surface of tungsten exceeds its melting threshold with temperature lower than the melting point. Concomitant phenomenon including fondant motion, droplet sputtering and vapour layer formation will also damage the target. Research shows tungsten block initiates melting under heat load of 2 GW/m^3 for 2 ms.

Experiments need to be done to figure out the damage behaviour of tungsten target in accelerators to ensure stable operation of the accelerator and to get greater X-ray yield.

EXPERIMENT SETUP

Experiment Platform

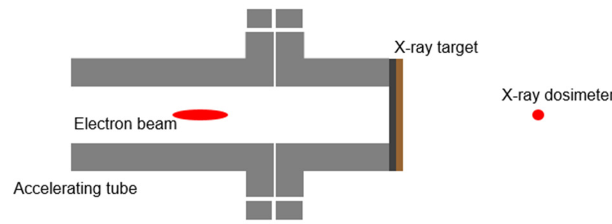

Figure 1: Schematic of the experiment.

Figure 1 shows the schematic of the experiment. An S-band 6 MeV standing-wave accelerator with 6 pairs of accelerating cells was used. The target of 2 mm W+0.5 mm Cu was adopted. The target was assembled with a flange for vacuum sealing. An X-ray dosimeter was set at 1m in front the target to monitor the dose rate during the course of the experiment. Target failure or related components failure can be detected in reference to the dose rate abnormity. To expedite the experiment, water cooling system was stopped in the experiment.

Electron Beam Loading

The pulsed electron beam came with a constant pulse width of 4.3 μs. The mean power of the electron beam is regulated by changing the repetition frequency. The electron current flowing through the target was measured every time we changed the repetition frequency.

Table 1: Electron Beam Loading Modes

Parameters	Stage I	Stage II	Stage III
Pulse Width(μs)	4.3	4.3	4.3
Repetition Frequency(Hz)	50	100	220
Current through Target(mA)	160	158	159
Mean Current(μA)	34	69	151
Load Time(s)	80	137	248

Table 1 shows the electron beam loading modes. The loading process includes three stages. First, the electron beam with repetition frequency of 50 Hz and mean current

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of 34 µA was loaded on the target to preheat the target. After 80 seconds, the repetition frequency was increased to 100 Hz and the mean current rose to 69 µA in turn. 69 seconds later, the repetition frequency was increased to 220 Hz at full power with mean current of 151 µA. After 248 seconds, X-ray dose rate suddenly dropped to zero. We stopped the experiment and removed the target for surface topography analysis. Figure 2 shows the results of X-ray dose rate monitor in the course of the experiment. X-ray dose rate is proportional to the mean current of the electron beam.

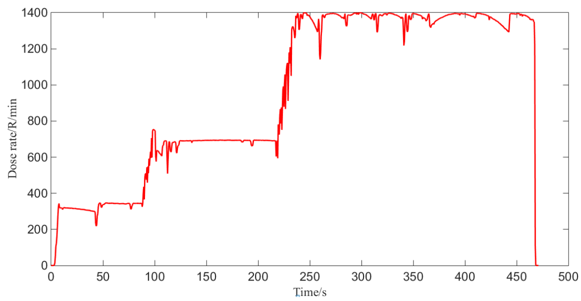

Figure 2: X-ray dose rates during the experiment.

RESULTS

Target Temperature Behaviour

Finite element analysis software ANSYS was used to calculate the transient thermal behaviour of the target. To avoid enormous calculations, average power input was adopted to replace pulsed power input. Figure 3 shows the maximum transient temperature of the target under average power input during the course of the experiment. Due to the absence of cooling water, the maximum temperature in the target keeps rising and soars every time when increasing the average power input. The maximum temperature under average power input reaches 2365 °C.

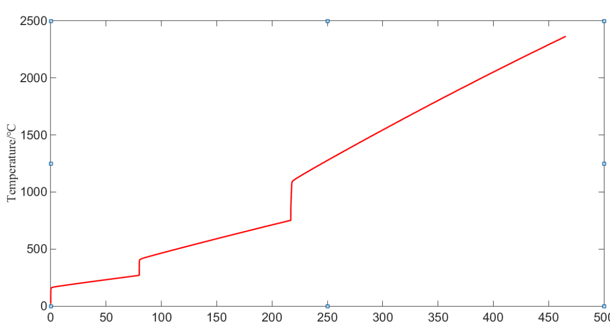

Figure 3: Maximum transient temperature within the target under average power input.

Figure 4 shows the temperature distribution of the target surface under average power input at the final state. The surface temperature reaches more than 1600 °C overall with a maximum of 2362.4 °C in the centre of the target surface. Recrystallization is assumed to occur on the target.

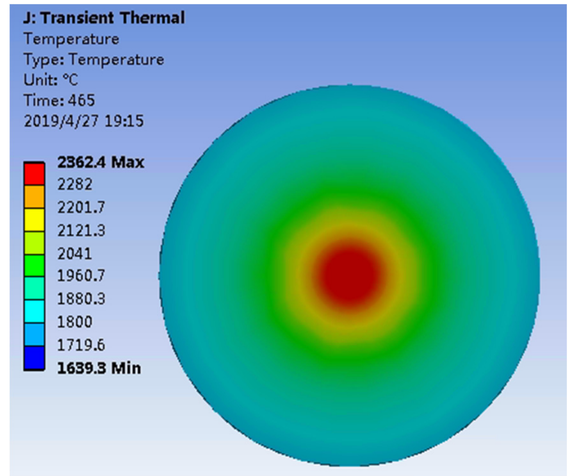

Figure 4: Final state temperature distribution of the target surface under average power input.

Target Surface Appearance

Identical tungsten target that is not irradiated by electron beams or other irradiations is adopted as the control group. White light interferometer (WLI) was used to examine the surface morphology of experimental target and the control group at first. The examination results of the two targets are showed in Fig. 5 and Fig. 6, respectively. The traces of rolling are evenly distributed on the surface of the control group. A bulge with a diameter of around 1 mm is observed on the surface of the experimental target. The elevation of the highest point is measured as 56 µm. An annular depression of 5-8 µm is observed surrounding the bulge. Figure 7 shows the specific deformation data of the experimental target.

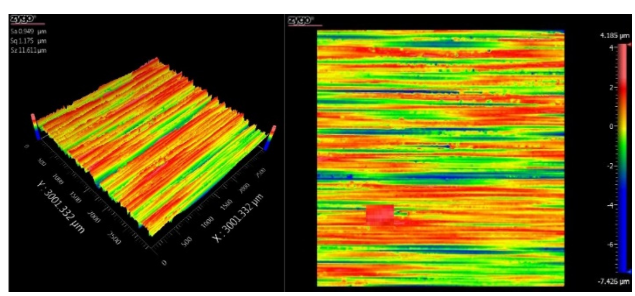

Figure 5: Surface morphology of the control group surface utilizing WLI.

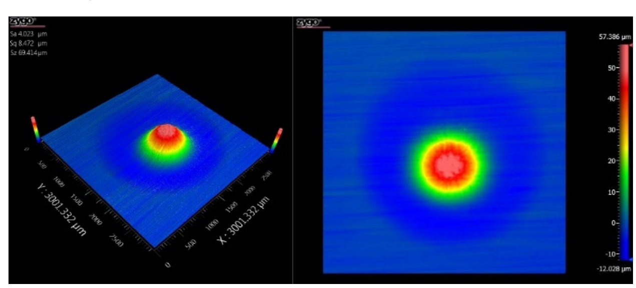

Figure 6: Surface morphology of the experimental target utilizing WLI.

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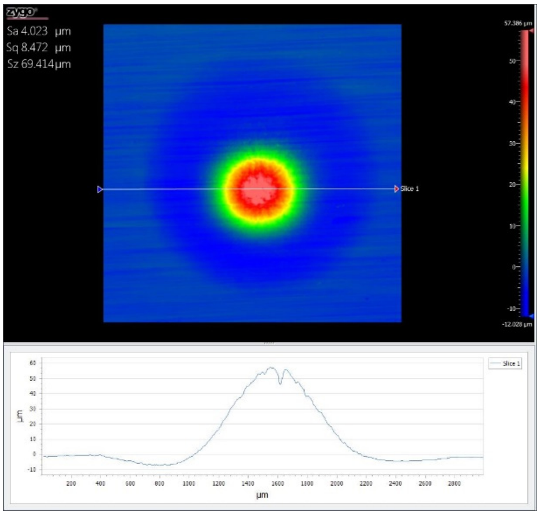

Figure 7: Specific deformation data of the experimental target surface utilizing WLI.

The morphology of the experimental target surface was further examined with scanning electronic microscope (SEM). Figure 8 shows the examination results of the centre of target surface utilizing SEM with different levels of magnification. The surface of the bulge appears rough, the crystal lattices expand and squeeze against each other, several cracks can be observed along the grain boundaries. Recrystallization occurs on the surface centre. Etching phenomenon causing by tungsten melting and fatigue cracking are not observed. Target surface morphology examination results show consistence with the temperature results in simulations.

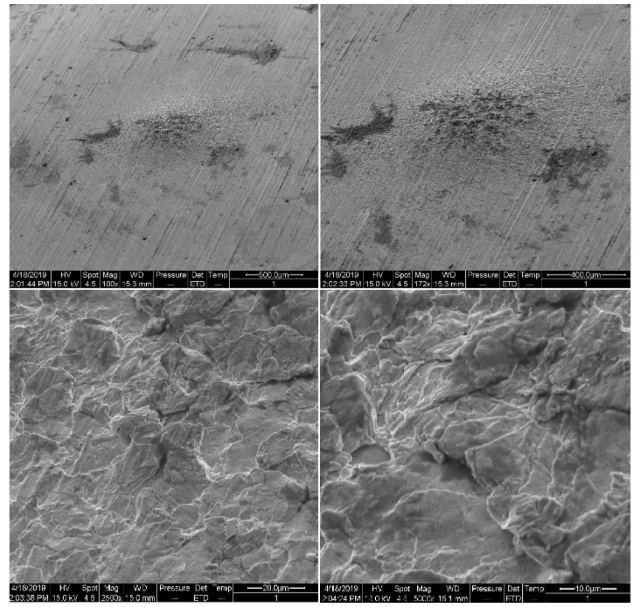

Figure 8: Surface morphology of the experimental target with different levels of magnification utilizing SEM.

CONCLUSION

Recrystallization occurs on the surface of tungsten target after loading 6 MeV electron beam with repetition frequency of 220 Hz, pulse width of 4 µs and mean current of 151 µA for 248 s without cooling system. Recrystallization is a form of damage behaviour of the tungsten X-ray targets. Transient temperature calculations show high accuracy. More properties of damage behaviours of different material targets require further experiments.

REFERENCE

[1] Qiang Gao and Hao Zha, “Design and Optimization of the Target in Electron Linear Accelerator”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPWA016, pp. 3663-3665.

[2] David P. Pritzkau, “RF Pulsed Heating”, Ph.D. thesis, Stan ford Linear Accelerator Centre, Stanford, CA 94309, 2001.

[3] Shen, Tielong, Yong Dai, *et al.*, “Microstructure and tensile properties of tungsten at elevated temperatures”, Journal of Nuclear Materials, vol. 468, pp. 348-354, 2016.

[4] Jin, Ming *et al.*, “Thermal and stress analysis of window target or accelerator-driven sub-critical system during beam trip transients”, Progress in Nuclear Energy. vol. 85, pp. 325-332, 2015.

[5] Jemila Habainy *et al.*, “Fatigue properties of tungsten from two different processing routes”, Journal of Nuclear Materials pp. 1-9, 2017.