ScienceDirect

Journal of Alloys and Compounds

Volume 923, 25 November 2022, 166411

Study on the damage of $Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ amorphous and crystalline alloys irradiated by high intensity pulsed ion beam

Na Li [a], Lisong Zhang [a], Xiaonan Zhang [b], Xianxiu Mei [a], Jianbing Qiang [a], Xiaona Li [a], Younian Wang [a], Sergey K. Pavlov [c], Gennady E. Remnev [c], Vladimir V. Uglov [d]

[a] Key Laboratory of Materials Modification by Laser, Ion and Electron Beams, Ministry of Education, Dalian University of Technology, Dalian 116024, China

[b] School of Science, Dalian Jiaotong University, Dalian 116028, China

[c] National Research Tomsk Polytechnic University, Tomsk 634028, Russian Federation

[d] Belarusian State University, Minsk 220030, Belarus

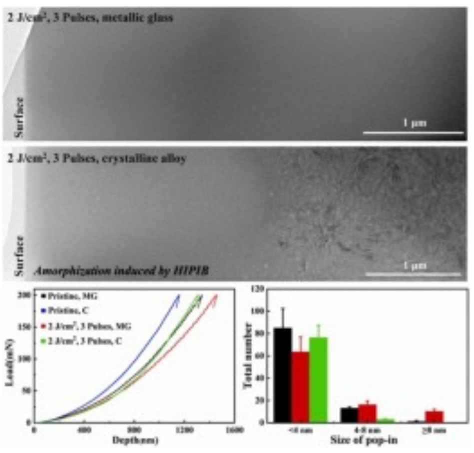
Received 16 May 2022, Revised 15 July 2022, Accepted 19 July 2022, Available online 21 July 2022, Version of Record 28 July 2022.

https://doi.org/10.1016/j.jallcom.2022.166411

Abstract

$Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ amorphous and crystalline alloys were irradiated by high intensity pulsed ion beam to investigate the effects of transient high thermal load irradiation on their microstructure, surface reflectivity and nano-hardness. When the high temperature caused by transient thermal shock did not reach the melting temperature of the alloys, there was no obvious change in the phase-structure of amorphous and crystalline alloys, and irradiation had little impact on surface reflectivity and nano-hardness. When the temperature exceeding the melting temperature, amorphous alloys still maintained amorphous strtucture, and more free volumes generated by remelting and rapid solidification process, resulting in the reduction of nano-hardness; while micrometer-sized amorphization appeared in the crystalline counterpart, which also reduced the nano-hardness. Compared with molybdenum, a candidate material of the first mirror, there was no crack on the surface and less change of surface reflectivity in amorphous and crystalline alloys.

Graphical Abstract



Introduction

Fusion reactors have a complex environment containing neutron irradiation, plasma irradiation, and transient high thermal load irradiation up to 1 GW/m^2 [1], [2], leading to structural damage and performance degradation of service materials. Traditional crystalline materials are subject to deteriorating behaviors such as blistering, cracking and hardening during long-term service [3], [4], [5], which severely limit their efficiency and service life. Amorphous alloys, known as metallic glasses (MG), have a unique short-range ordered, long-range disordered structure without common crystal defects such as grain boundaries and dislocations, and exhibit high strength, high fracture toughness and good corrosion resistance, etc [6], [7]. Zr-based bulk amorphous alloys break through the size limitations of earlier amorphous alloys (often powder, wire, strip and flake), with a maximum critical size of d_{max} up to 73 mm [8] and a high glass formation ability (GFA), presenting a broad application prospect. In particular, they retain a lot of free volumes by rapid cooling during preparation, which are capable of providing more locations and channels for ion diffusion [9], considered to have good structural self-healing efficiency.

Currently, many researchers have focused on the study of the ion irradiation resistance of Zr-based bulk amorphous alloys to examine their structural stability and irradiation damage mechanisms under various ions bombardment such as Xe ions and He ions [10], [11], [12], [13]. Considering their sensitivity to temperature due to the sub-stable structure, they often experience transient high thermal load shocks resulting from unstable rupture of the plasma when applied to plasma-facing materials in fusion devices, thus it is extremely valuable to study their resistance to transient thermal shocks.

Combining with ion irradiation and strong thermal radiation, high intensity pulsed ion beam (HIPIB) is characterized by short pulses ($t \le 1$ μs) as well as high power intensity (up to several hundred GW/m^2) [14], and capable of rapid energy deposition on the material surface to achieve a rapid rise of material temperature with a heating rate up to 10^{10} K/s [15]. HIPIB can cause materials to melt, vaporize and ablate on timescales of tens to hundreds of nanoseconds [16], [17], produce sub-stable phase structures such as nanocrystal [18] and amorphous [19], and form craters [20], cracks [21] and other damages during the subsequent rapid solidification process, causing the properties of the material surface to change. Thus, HIPIB is suitable for simulating transient thermal shocks triggered by factors such as plasma instability in fusion devices [22], [23]. In this paper, $Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ bulk amorphous alloy with high GFA (d_{max} = 20 mm) and high thermal stability (supercooled liquid region: ΔT_x = 119 K) [24] was irradiated by HIPIB, and compared with its crystalline counterpart to investigate the differences in transient thermal shock resistance between $Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ amorphous and crystalline alloys, which will provide data to support the selection and research of materials in fusion reactors.

Section snippets

Materials and methods

Alloys ingot of nominal composition $Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ amorphous alloys was manufactured by arc melting of elemental Zr, Cu, Al, Fe of> 99.9 wt.% purity under high purity argon atmosphere. The alloy ingot was remelted four times to achieve compositional homogeneity. Then the melted alloy was cast into a water-cooled copper mold with a form of 3 mm diameter rod [25], [26]. After cutting, amorphous alloys of 2 mm thickness formed. Based on the differential scanning calorimetery (DSC) result in...

Calculation results

Fig. 1 shows the distributions of dpa and ions concentrations in $Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ alloys with the irradiation conditions of 0.3 J/cm^2, 300 pulses and 2.0 J/cm^2, 3 pulses, simulated by SRIM in full-cascade mode. The projected ranges of carbon and proton were 600 nm and 1600 nm, and corresponding ions concentrations peak appeared at 360 nm and 1300 nm. The distribution range of dpa was close to that of carbon concentration, indicating dpa was caused basically by cascade collisions of carbon...

Conclusions

$Zr_{63.5}Cu_{23}Al_9Fe_{4.5}$ amorphous and crystalline alloy were irradiated by high intensity pulsed ion beam to investigate the effects of transient high thermal load irradiation on their microstructure, surface morphology and reflectivity and nano-hardness, the following conclusions were obtained.

(1) When the temperature rise caused by transient thermal shock did not reach the melting temperature of two types alloys (energy density ≤ 0.5 J/cm^2), the structure of the amorphous and crystalline alloys...

...

CRediT authorship contribution statement

Na Li: Software, Writing - original draft. **Lisong Zhang:** Investigation. **Xiaonan Zhang:** Investigation. **Xianxiu Mei:** Conceptualization, Methodology, Funding acquisition, Project administration. **Jianbing Qiang:** Resources. **Xiaona Li:** Methodology. **Younian Wang:** Supervision. **Gennady E. Remnev:** Resources, Writing – review & editing. **Vladimir V. Uglov:** Resources, Writing – review & editing....

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 11975065 and No. 11911530086)....

References (53)

S.J. Zinkle *et al.*
Materials challenges in nuclear energy
Acta Mater. (2013)

M. Qu *et al.*
Damages on pure tungsten irradiated by compression plasma flows
Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At. (2019)

M. Miyamoto *et al.*
Systematic investigation of the formation behavior of helium bubbles in tungsten
J. Nucl. Mater. (2015)

X. Mei *et al.*
Effect on structure and mechanical property of tungsten irradiated by high intensity pulsed ion beam
Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At. (2017)

Q. Yang *et al.*
Microscopic evolution of pre-damaged and undamaged tungsten exposed to low-energy and high-flux helium ions
Nucl. Instrum. Methods Phys. Res, Sect. B: Beam Interact. Mater. At. (2014)

C.A. Schuh *et al.*
Mechanical behavior of amorphous alloys
Acta Mater. (2007)

A. Nair *et al.*
An experimental case study on corrosion characterization of Cu46Zr40Ti8.5Al5.5 metallic glass
J. Non-Cryst. Solids (2019)

A. Inoue *et al.*
Recent development and application products of bulk glassy alloys
Acta Mater. (2011)

J. Carter *et al.*
Effects of Cu ion irradiation in Cu50Zr45Ti5 metallic glass
Scr. Mater. (2009)

X.L. Bian *et al.*
Manipulation of free volumes in a metallic glass through Xe-ion irradiation
Acta Mater. (2016)

View more references

Cited by (1)

Effect on microstructure of Fe<inf>80</inf>B<inf>13</inf>Si<inf>7</inf> metallic glass irradiated by high intensity pulsed ion beam and He ions
2022, Surface and Coatings Technology

Show abstract

Recommended articles (6)

Research article
Relaxation behavior of an Al-Y-Ni-Co metallic glass in as-prepared and cold-rolled state
Journal of Alloys and Compounds, Volume 923, 2022, Article 166313

Show abstract

Research article
Preparation of highly ionic conductive lithium phosphorus oxynitride electrolyte particles using the polygonal barrel-plasma treatment method
Journal of Alloys and Compounds, Volume 923, 2022, Article 166350

Show abstract

Research article
Plasma-modified flaky FeSiAl alloy for efficient growth of carbon nanotube arrays with high carbon conversion rate
Journal of Alloys and Compounds, Volume 923, 2022, Article 166453

Show abstract

Research article
Unveiling the phonon effect on the narrow-band deep-red emission from solution-combustion synthesized Mn^{4+} doped $CaYAlO_4$ microcrystals
Journal of Alloys and Compounds, Volume 923, 2022, Article 166280

Show abstract

Research article
A novel strategy to accelerate electrochemical kinetics in polymorphic Nb_2O_5 nanosheets for highly stable and rate-capable lithium storage
Journal of Alloys and Compounds, Volume 923, 2022, Article 166397

Show abstract

Research article
Significantly improved dielectric properties of tin and niobium co-doped rutile TiO_2 driven by Maxwell-Wagner polarization
Journal of Alloys and Compounds, Volume 923, 2022, Article 166371

Show abstract

View full text