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Influence of High Energy Particles on Copper and Stainless Steel in Fusion Reactor Materials

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Abstract

Many studies were focused on the effect of fusion plasma particles onto the structural materials of future nuclear fusion reactor. In this paper, the effect of the products of the first generation fuel reaction on structural fusion materials as copper and 316-stainless steel target materials was studied. Firstly, the effect of 14.1 MeV neutrons produced from D-T neutron generator for different irradiation time equal to 10, 20, 30, 50 and 60 minutes was investigated. Hence, this effect was analyzed and characterized by X-ray diffraction analysis, surface roughness tester, scanning electron microscope and Vickers hardness. Secondly, the effect of 3.5 MeV α -particles on these target materials by different incident angles equal to 0° , 30° , 45° , 60° and 85° using SRIM code was studied. Also, SRIM code was used for calculation α -particles trajectories, projected and straggle ranges, skewness, kurtosis, target ionization / phonons and total displacements for copper and 316- stainless steel target materials.

Keywords: D-T neutrons generator, Cu and 316-Stainless Steel, Surface Roughness, Vickers Hardness, SRIM

Introduction

Plasma interactions with the plasma facing components (PFCs) is one subject of intensive research in tokamaks as International Thermonuclear Experimental Reactor (ITER) and fusion reactors. The most important issues for ITER and the next step of the fusion devices are the interaction processes of plasma surface with large plasma heat load and particle fluxes [1, 2]. The erosion of PFCs borders the life time of divertor because of the eviction of eroded material from the exposed surface so that they have to withstand a high neutron flux and then a high thermal energy away from the first wall surface. In fusion reactors, the common material used as a structural one is stainless steel alloy and also copper material acts as a heat sink. With respect to the vacuum vessel, the major part is covered with primary first wall that composed of a thick shield block (stainless steel alloy) and a heat sink (copper alloy) cooled by water flowing in stainless steel tubes. The first wall absorbs the heat radiation from the plasma as well as provides neutron shielding [3, 4]. The main goal of choice copper for both first wall and divertor ITER due to its good thermal conductivity [5, 6]. The copper function in the first wall is mainly to dissipate the heat produced as a result of plasma disruptions.

Generally, the metals and alloys that are irradiated by energetic neutrons have substantial changes in their physical and mechanical properties [7-9] due to the irradiation induced the microstructures. The microstructural upgrowth is directly or indirectly dependent on the type of irradiation (e.g. mass and energy of projectile particles), damage rate, irradiation temperature, chemical composition of the materials and their initial microstructure. Different stainless steel materials as 304L, 316, and 316L can be used for the fabricated vacuum vessel, first wall - plasma facing components, structures of mechanical support, and other subsystems [10]. Due to the 316-stainless steel grade materials superior

mechanical and corrosion resistant properties, they can be used primary structural material candidates in nuclear fusion reactor components [11]. The light elements as the hydrogen isotopes, protium, deuterium, and tritium, have been used as the fuels in the nuclear fusion reactor [9]. So that, many studies were done on different materials to be used safely in this reactor. Hence, the first-generation fusion fuel nuclear reaction at the lowest energy is [12]:

In magnetic confinement systems due to the neutrality of neutron, it is not affected by the presence of the magnetic field and then escapes immediately from the reactor volume, however the charged α -particle is confined. Then, the kinetic energy of these escaping fast neutrons will be converted into heat in a blanket and then into electricity using steam [13]. With respect to the reactants, the common available occurring hydrogen isotope in nature is a deuterium. Also, tritium was a natural isotope of hydrogen with a half-life of 12.32 years leading it to be expensive and a hard to find, store, and produce. The second-generation nuclear fusion fuel reaction is fusing of the two nuclei of deuterium. This reaction has two branches that occur with nearly equal probability:

The reactions (1), (2) and (3) were common in research, industrial, and military applications. The optimum energy which is used to initiate the D-D reaction was 15 keV which slightly higher than that for D-T reaction. The second-generation fusion fuel is [12]:

Various methods were developed for simulating the radiation damage in different materials especially used in nuclear reactors [14]. A Monte-Carlo SRIM code that is based on the assumption of binary collision in which the atoms' collisions can be approximated by binary elastic collisions described by an interaction potential. SRIM is abbreviated for Stopping and Range of Ions in Matter or TRIM (for ion transport in matter) is widely used to calculate the radiation damage with two basic options of damage as Quick Calculation and Full Cascade simulation [15]. The ions - target atoms interaction can be divided into the binary elastic and inelastic collisions. The elastic interaction, ion - target nucleus, is related to the nuclear stopping cross section leading to an angular scattering of the ion and an energy loss due to the momentum transfer. The inelastic interaction, ion - target electrons, is related to the electronic stopping cross section [16]. Different studies were used SRIM code to simulate and compute the interaction of different incident particles with low and high energies on various materials to investigate the target damage processes [17-19].

This study aims to investigate the interaction of the products of the first-generation nuclear fusion fuel reaction, neutrons (14.1 MeV) and α -particles (3.5 MeV), with copper and 316- stainless steel (316-SS) as plasma facing components used in fusion reactors experimentally and by SRIM code. The previous study carried on the effect of the second nuclear fusion fuel reaction products, protons (14.7 MeV) and α -particles (3.6 MeV), using SRIM on C, Ti, Zr, Mo, Ta, and W materials was completed [20]. Also, the effect of first generation nuclear fusion fuel reaction on W and C experimentally using D-T neutron generator [21].

1- Experimental Results of 14.1 MeV Neutrons

In this experiment, copper and 316-SS samples were irradiated by 14.1 MeV neutrons which produced from (D-T) reaction using neutron generator MP 320, Thermo Scientific™ located at Miners Laboratory- Nuclear Research Center - Egyptian Atomic Energy Authority. This generator of (D-T) neutrons tube has very low power requirements and the produced mono-energetic neutrons of 14.1 MeV with flux 1.3×10^8 n/s and total number of neutrons generated per one hour 1.75×10^9 n/cm².

Radiation damages produced by an elastic collision with the lattice atoms that will result in swelling, hardening and some other material degradation. These samples were irradiated with different neutron doses time equal to 10, 20, 30 and 50 minutes. The Cu sample dimensions was 20 mm length, 20 mm wide and thickness equal to 10 mm, while the 316-SS sample dimensions was 10 mm length, 10 mm wide and thickness equal to 5 mm. After irradiation the samples by the neutrons, the samples were analyzed by using scanning electron microscope, XRD apparatus, surface roughness tester and Zwick Vickers hardness apparatus.

1.1- Scanning Electron Microscope (SEM)

The irradiated samples were observed under SEM with 1500 times magnification that located at Nuclear Research Center, Atomic Energy Authority, Inchas, Egypt. Figures (1: a-e), (1: a'-e') show the surface morphology of irradiated Cu and 316-SS samples observed under SEM for 0, 10, 20, 30 and 50 minutes neutrons dose time, respectively. From SEM - Cu images, it was seen that the blank sample showed as a clean, homogenous, and smooth surface. After neutrons irradiation, there was a dislocation channels appeared in sample (b) and increased more in sample (d). But in sample (c), the dislocation loops were observed whereas in sample (e), the surface were decreased and an enhancement in the number of dislocations and voids. From SEM - 316-SS images, it was clear that the blank sample showed also as smooth surface. But after neutrons irradiation, it was some localized stains due to the interaction of neutrons with stainless alloy that contains different elements. In general, 316-SS was less distortion than Cu.

Fig. (a) Cu SEM image for blank	Fig. (a') 316-SS SEM image for blank

Fig. (b) Cu SEM image for 10 min.	Fig. (b') 316-SS SEM image for 10 min.

Figures (1) (a - e) Cu and (a' - e') 316-SS surface morphologies observed by SEM for blank and 10, 20, 30 and 50 minutes neutrons dose, respectively.

1.2- X-ray diffraction

The samples were measured using x-ray diffractometer placed at National Center for Research and Radiation Technology, Atomic Energy Authority, Nasr City, Egypt. The Shimadzu XRD-6000 is an X-ray diffractometer with Cu-K α radiation source of 0.1546 nm wavelength, NaI detector and tungsten filament operated with a voltage of 40 kV and a current of 30 mA that used to analyze the crystalline states under normal atmospheric conditions. It is a nondestructive analytical technique in which the focused X-rays on a sample fixed on the axis of the spectrometer were diffracted by the sample. XRD patterns were obtained at a scan rate of 2° per minute on the diffractometer. The changes in the intensities of diffracted X-ray are measured, recorded and plotted against the rotation angles of the sample. Hence, the peak intensities and positions associated with this pattern enables qualitative analysis, lattice constant determination and/or stress determination of the sample that are analyzed by computer. Qualitative analysis may be conducted on the basis of peak height / area. The peak angles and profiles may be used to determine the particle diameters and degree of crystallization, and are useful in conducting precise X-ray structural analysis. The Sherrer equation can be used to calculate the particle size in the XRD pattern, given by [22]:

$$d = \frac{k \lambda}{\beta \cos \theta} \quad (5)$$

Where d , λ , β , and θ are the crystal size (nm), X-ray wavelength (1.5406 Å), full width at half maximum (radians) and diffraction angle, respectively.

Figures (2) and (3) show the different neutron dose times (minutes) versus the intensity (a.u) for Cu and 316-SS, respectively. In case of Cu, it is clear that the intensity decreased with time of neutron dose until 30 min. and then decreased to 60 minutes. For 316-SS, the intensity was decreased with increasing the neutron exposure time.

Figure (2) neutron dose times (minutes) versus the intensity (a.u) for Cu samples.

Figure (3) neutron dose times (minutes) versus the intensity (a.u) for 316-SS samples.

Tables (1) and (2) presented the XRD parameters including diffraction angle, FWHM in degree and radian, and the calculated crystal size in nm for the blank and neutrons irradiated samples, respectively. It is clear that the crystal size of neutrons irradiated sample with dose time equal to 30 min. and more was higher than the blank Cu sample. For 316-SS, the crystal size of neutrons irradiated samples with doses time equal to 10, 20, and 50 min. were higher than the blank 316-SS sample. This means an increase in the width of the diffraction peak relative to un-irradiated samples. Also, the crystal size in Cu was higher than that in 316-SS and Cu irradiated samples were more effected by neutrons than 316-SS irradiated samples. From the equation (5), FWHM is inversely proportional to crystallite size and it was observed in the two tables.

Table (1) XRD parameters for blank and neutrons irradiated Cu samples

Neutrons dose time (min.)	2θ	FWHM ($^{\circ}$)	FWHM (β) radian	Crystal size (nm)
0	50.8056	0.3498	0.0061	27.9495
10	43.1411	0.4258	0.0074	22.3029
20	50.5276	0.5578	0.0097	17.5072
30	50.9206	0.2216	0.0039	44.1399
50	50.9262	0.251	0.0044	38.9706
60	50.438	0.2383	0.0042	40.9648

Table (2) XRD parameters for blank and neutrons irradiated 316-SS samples

Neutrons dose time (min.)	2θ	FWHM ($^{\circ}$)	FWHM (β) radian	Crystal size (nm)
0	74.805	0.57	0.00994	19.5041
10	74.912	0.568	0.00991	19.5867
20	74.845	0.57	0.00994	19.5094
30	75.0933	0.5867	0.01023	18.9855
50	74.7662	0.559	0.00975	19.8828
60	74.855	0.59	0.01029	18.8492

1.3- Surface roughness

Surface roughness was defined as a component of surface texture and fine irregularities that were produced during a machining process (grinding, polishing etc.). If these deviations were small, the surface was smooth; if they were large, the surface was rough. Figure (4) shows the comparison between the surface roughness (μm) versus the neutrons dose times (minutes) for Cu and 316-SS samples, respectively. It was clear that after neutron irradiation, Cu surface roughness was increased at sample of 10 min. irradiation time than blank one and then decreased until 20 min. and increased to reach the value of blank sample at 60 min. irradiation time. This means that the Cu surface was rough for neutrons dose irradiation after long time of operation. If the dose time was equal to 20 minutes, the Cu surface was smooth. With respect to 316-SS, the roughness value was increased with small value than blank sample and still constant with the neutrons irradiation. This indicates that the surface was rough with neutrons irradiation. In general, the Cu surface roughness was affected largely than 316-SS.

Figure (4) Comparison between the surface roughness versus the neutrons dose times for Cu and 316-SS samples.

1.4- Vickers hardness

The indentation Vickers test is a non-destructive method and didn't depend on the indenter size that used to describe the hardness of different materials. This test is based on the ability of material under check to resist plastic deformation from a standard source. The hardness of copper and stainless-steel samples was measured using Vickers hardness tester (Zwick - 3212) in Nuclear Research Center, Atomic Energy Authority, Inchas, Egypt as shown in figure (5). The mean hardness (H_v) was calculated from equations:

$$H_v = \frac{P}{A} = \frac{1.852 \cdot P}{d^2} \quad (6)$$

$$d \text{ (mm)} = d' \times 7.353 \times 10^{-4} \quad (7)$$

$$A = \frac{d^2}{2 \sin\left(\frac{136^\circ}{2}\right)} \quad (8)$$

Where, H_v (kg/mm^2) is the mean Vickers hardness, P (kg) is the force applied to the diamond and equal to 1kg (for Cu) and 2kg (for 316-SS), A (mm^2) is the surface area of the resulting indentation and d (mm)² is the average diagonal length left by the indenter.

Figure (5) Zwick - 3212 Vickers hardness tester machine.

Figure (6) shows the effect of 14.1 MeV neutrons different dose times on the hardness of Cu and 316-SS for blank and irradiated samples. For 316-SS, it was clear that before and after irradiation time equal to 20 min., its hardness decreases. Also, the irradiated 316-SS samples have lower hardness values than the blank sample. But it was the opposite behavior in case of Cu irradiated samples and also the blank sample has a higher hardness value than irradiated ones. The increase in hardness indicated to the interaction occurred between dislocations and loops that observed even at the lowest damage levels. These defects are observed using SEM to match with the hardness measurements for Cu and 316-SS samples.

Figure (6) Mean Vickers hardness versus neutrons dose time for Cu and 316-SS samples.

2- SRIM Simulation of 3.5 MeV α -Particles

Using SRIM 2013, the effect of 3.5 MeV α -particles on copper and 316-SS steel samples with different incident angles equal to 0° , 30° , 45° , 60° , and 85° can be simulated. The target materials, Cu and 316-SS, with the same thicknesses equal to $20\ \mu\text{m}$. The mechanisms of slowing down for α -particles and dissipating their energy due to the impact on solid targeting materials as a result of the nuclear and electronic energy losses due to elastic and inelastic collisions, respectively.

2.1- SRIM of 3.5 MeV α -particles trajectories with different angles on Cu and 316-SS

Figures (7: a-e) and (8: a'-e') show the α -particles trajectories with angles equal to 0° , 30° , 45° , 60° , and 85° due to the impact on copper and 316-SS target materials, respectively. It was clear that the trajectory penetration in case of copper more than that 316-SS. Also, it was obvious that the penetration range in a tested target material decreases by increasing the atomic mass of target materials.

Figures (7: a-e) and (8: a'-e') Show α -particles trajectories impact on Cu and 316-SS target materials with angles 0°, 30°, 45°, 60°, and 85°, respectively.

2.2- SRIM of 3.5 MeV α -particles distribution with different angles on Cu and 316-SS

Figures (9: a-e) and (10: a'-e') show the α - particles distribution ranges and its parameters such as mean range, straggling, skewness and kurtosis incident with angles equal to 0° , 30° , 45° , 60° , and 85° on copper and 316-SS target materials, respectively. Straggling, skewness and kurtosis are the quantities related to the second, third and fourth moments of the ion distribution, respectively. It was clear that the α - particles range in Cu target was higher than that in 316-SS target material. Also, it was obvious that the α - particles range in a tested target material decreases by increasing the atomic mass of target materials and the incident angle. Moreover, the straggle for Cu target was lower than 316-SS and it increases with increasing the incident angle of α - particles in the target materials. At angle 0° , the mass of α - particles distribution was concentrated on the right (negative skewness) and 316-SS has more negativity in skewness. By increasing the incident angle, there was a decrease in negativity until reaching 85° at which the mass of α - particles distribution is concentrated on the left (positive skewness).

Figures (9: a-e) and (10: a'-e') α-particles distribution impact on Cu and 316-SS target materials with angles 0°, 30°, 45°, 60°, and 85°, respectively.

Figure (11) shows the α-particles projected (μm) and straggle (Å) ranges compared with different incident angles for Cu and 316-SS target materials. There was an opposite behavior between these ranges for the both target materials. But, the Cu target has higher projected range and lower straggle range than 316-SS target. Also, there was a decrease in projected range and an increase in straggle range with increasing the incident angle for Cu and 316-SS targets.

Figure (11) α -particles projected and straggle ranges compared with different incident angles for Cu and 316-SS target materials.

2.3- SRIM of 3.5 MeV α -particles ionization with different angles on Cu and 316-SS

Energy loss of α -particles to Cu and 316-SS target electrons is known as the ionization losses (electronic energy losses). Figures (12: a-e) and (13: a'-e') show the Cu and 316-SS target ionization due to the incident of α -particles by different angles equal to 0°, 30°, 45°, 60°, and 85°, respectively. As a result of the losses due to ionization that cause the target damage where the charge can build up until macroscopic damage may occur e.g. cracking. Also, the ionization losses into the target caused by recoiling target atoms (blue curve appears small with respect to ionization). The recoiling atoms have much less interaction with the faster moving target electrons so that they move relatively slowly. It was clear that the target damage decreases by increasing the angle of incident α -particles. Moreover, the intensity of energy loss in case of Cu is lower than that of 316-SS target material.

Figures (12: a-e) and (13: a'-e') Distribution of Cu and 316-SS target ionization due to the incident of α -particles by angles 0° , 30° , 45° , 60° , and 85° , respectively.

2.4- SRIM of 3.5 MeV α -particles 3D phonons with different angles on Cu and 316-SS

Assume an incident α -particle has atomic number (Z_1) and energy (E). It has a collision within the Cu target with atomic number (Z_2), as example - see fig. (14). After happening the collision, the incident α -particle has energy (E_1) and the knocked-on-atom has energy (E_2). Concerning the target, there are energies as the displacement energy (E_d), the binding energy of a lattice atom to its site (E_b), and the

final energy of a moving atom, below which it is considered to be stopped (E_f). There are three processes can be taking place which were the displacement, vacancy, and phonons. (i) the displacement can be occurred if $E_2 > E_d$ (the strike atom is given enough energy to leave the site and then the generated heat was dissipated to the surroundings). (ii) a vacancy occurs if $E_1 > E_d$ and also $E_2 > E_d$ (so both atoms have enough energy to leave the site and then become moving atoms of the cascade). Hence, the energy, E_2 , of atom Z_2 is reduced by E_b before it has another collision. (iii) If $E_2 < E_d$, then the knocked-on-atom does not have enough energy and will vibrate back to its original site, releasing phonons with energy (E_2). (iv) Finally, if $E_1 < E_d$ and $E_2 < E_d$, then Z_1 becomes an interstitial and phonons will be released with energy ($E_1 + E_2$). If a target under test consists of several different elements in it (as 316 - stainless steel case study), and each has a different displacement energy, then E_d will change for each atom of the cascade hitting different target atoms.

Figure (14) Schematic of energy transfer via elastic atomic collision.

The displacement energy (E_d) is defined as the minimum amount of energy which must be transferred to the Cu or 316-SS target atom to knock it out of its lattice site and far enough away so it doesn't immediately fall back into this lattice hole. If this transferred energy was less than (E_d), then it was assumed that the Cu or 316-SS atom returns to its lattice site and its recoil energy is transferred into target phonons. Figures (15: a-e) and (16: a'-e') show the Cu and 316-SS target phonons due to the incident of α -particles by different angles equal to 0° , 30° , 45° , 60° , and 85° , respectively. It was clear that total ionization for Cu or 316-SS is nearly the same and no change with different α -particles incident angles except 85° angle, it is increased rarely. Whereas, the total phonons for Cu target was higher than that for 316-SS target and, there is no change with α -particles incident angles 0° , 30° , 45° , 60° . But at angle 85° , they were decreased from 15.5 to 14.7 keV/ion and 11.4 to 11 keV/ion for Cu and 316-SS targets, respectively. In addition, total Cu target damage with α -particles incident angles 0° , 30° , 45° , 60° is the same (1.21 keV) and is higher than that of 316-SS target (0.9 keV/ion). But it decreased for both targets at α -particles incident angles 85° . This was because 316-SS target has several different elements (Cr, Mo, Mn, Ni, Fe), and then each of them has a various displacement energy, so that energy will change for each atom of the cascade hitting different target atoms.

Figures (15: a-e) and (16: a'-e') Distribution of Cu and 316-SS target phonons due to the incident of α -particles by angles 0°, 30°, 45°, 60°, and 85°, respectively.

2.5- SRIM of 3.5 MeV α -particles 3D total displacement with different angles on Cu and 316-SS

A replacement collision with energy (E_1) that released as phonons will occur if $E_1 < E_d$ and $E_2 > E_d$ and then the incoming atom will remain at the site. In the lattice site, the atom remains the same atom by exchange and this collision was common in single element targets with large recoil cascades. Figures (17: a-e) and (18: a'-e') show the Cu and 316-SS target total displacements due to the incident of α -particles by different angles equal to 0°, 30°, 45°, 60°, and 85°, respectively. It was clear that the average Cu target displacements, vacancies, and replacement collisions are nearly the same for different incident α -particles angles 0°, 30°, 45°, 60° and higher than that for 316-SS target. But at angle 85°, they are decreased for both target materials. So, the α -particles and recoiling atoms of Cu and 316-SS targets create 425 and 304 displacements/ α -particle, respectively. Of these, the simulation presented that there are 402 displaced atoms as vacancies and 23 as replacement collisions. Moreover, the resulted 300 and 4 displaced atoms due to vacancies and replacement collisions, respectively. So that the replacement collisions are about 6% and 2% of the total displacements for Cu and 316-SS target, respectively. Moreover, the vacancies are the remaining percentage for completing the total displacements.

Total Displacements

Total Displacements = 425 / Ion
 Total Vacancies = 402 / Ion
 Replacement Collisions = 23 / Ion

(a) 0° angle α -particles in 20 μm Cu thickness**Total Displacements**

Total Displacements = 304 / Ion
 Total Vacancies = 300 / Ion
 Replacement Collisions = 4 / Ion

(a') 0° angle α -particles in 20 μm stainless 316 thickness**Total Displacements**

Total Displacements = 428 / Ion
 Total Vacancies = 405 / Ion
 Replacement Collisions = 23 / Ion

(b) 30° angle α -particles in 20 μm Cu thickness**Total Displacements**

Total Displacements = 304 / Ion
 Total Vacancies = 300 / Ion
 Replacement Collisions = 4 / Ion

(b') 30° angle α -particles in 20 μm stainless 316 thickness**Total Displacements**

Total Displacements = 428 / Ion
 Total Vacancies = 404 / Ion
 Replacement Collisions = 23 / Ion

(c) 45° angle α -particles in 20 μm Cu thickness**Total Displacements**

Total Displacements = 303 / Ion
 Total Vacancies = 299 / Ion
 Replacement Collisions = 4 / Ion

(c') 45° angle α -particles in 20 μm stainless 316 thickness

Figures (17: a-e) and (18: a'-e') Distribution of Cu and 316-SS target total displacements due to the incident of α -particles by angles 0°, 30°, 45°, 60°, and 85°, respectively.

Conclusion

In this work, firstly the Cu and 316-SS were irradiated by 14.1 MeV neutrons with different doses times. It was concluded that 316-SS is less distortion than Cu using SEM. From XRD spectra, it was found that the crystal size in Cu was higher than 316-SS which meaning that Cu samples were more effected by neutrons. Also, the surface roughness of Cu was affected largely than 316-SS. It was concluded that the neutrons irradiation for Cu leads to enhancement the hardness due to interactions between loops and dislocations. Secondly, the effect of 3.5 MeV α particles with different incident angles on Cu and 316-SS were calculated using SRIM program. It was concluded that the penetration range in the Cu and 316-SS target materials decreases by increasing the atomic mass of target materials. While the target damage decreases by increasing the angle of incident α -particles. Moreover, the intensity of energy loss in case of Cu was lower than that of 316-SS target materials.

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