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DETERMINATION OF RADIATION SHIELDING PARAMETERS OF COCRFENITIALX ALLOYS BY USING RECENTLY DEVELOPED PHY-X/PSD AND EPIXS SOFTWARES

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Abstract

We calculated the radiation shielding parameters of CoCrFeNiTiAlx alloys which consist of mass attenuation coefficient, linear attenuation coefficient, mean free path, half-value layer, total atomic cross section, effective atomic number and effective electron number. For this, we used recently developed Phy-X/PSD and EpiXS softwares. We compared all the results with each other, and discussed the relationship between the results.

Key Words: Radiation attenuation parameters, CoCrFeNiTiAlx, Phy-X/PSD, EpiXS

Özet

CoCrFeNiTiAlx alaşımlarının kütle zayıflatma katsayısı, lineer zayıflatma katsayısı, ortalama serbest yol, yarı kalınlık değeri, toplam atomik tesir kesiti, etkin atom numarası ve etkin elektron sayısından oluşan radyasyon zırhlama parametrelerini hesapladık. Bunun için son zamanlarda geliştirilen Phy-X/PSD ve EpiXS yazılımlarını kullandık. Tüm sonuçları birbiriyle karşılaştırdık ve sonuçlar arasındaki ilişkiyi tartıştık.

Anahtar Kelimeler: Radyasyon zayıflatma parametreleri, CoCrFeNiTiAlx, Phy-X/PSD, EpiXS

1. Introduction

Development of modern technology increases the radiation applications in our daily lives such as agriculture, medical imaging and radiotherapy. This case makes it necessary to develop new, practical and applicable materials for the protection from the harms of radiation (Alım et al., 2022). As a result of this, it becomes important to research alternative shielding materials, and is still one of the most current issues (Şakar et al. 2019, Alım 2020a, Aygun et al. 2021a, Aygun and Aygun, 2021b).

It is among the preferred methods to examine the radiation shielding parameters while determining alternative shielding materials. These parameters are mass attenuation coefficients (MAC), linear attenuation coefficients (LAC), mean free paths (MFP), half-value layers (HVL), atomic cross sections (ACS), effective atomic numbers (Zeff) and effective electron densities (Neff). Recently, two new softwares except for WinXCOM (Gerward et al. 2001, 2004) have been developed in order to determine the radiation shielding parameters. The first is Phy-X/PSD software (Sakar et al. 2020) and the other is EpiXS software (Hila et al. 2021). Thus, the radiation shielding parameters for different materials can be obtained with the help of Phy-X/PSD and EpiXS softwares. However, we think that it would be useful to calculate the radiation shielding parameters simultaneously for the same material(s) by using Phy-X/PSD and EpiXS softwares.

High-entropy alloy (HEA) is a new alloy, and has been presented by Yeh et al. (2004) and Cantor et al. (2004) independently. High-entropy alloys (HEAs) can be alloys with 5 or more principal elements. HEAs have some advantages over other alloys such as good thermal stability, high hardness, high strength, high corrosion resistance, etc. (Yen et al. 2019; Cantor et al. 2004; Zhou et al. 2007; Qiu et al. 2020; Varalakshmi et al. 2008; Wang et al. 2008). HEA is one of the areas that has attracted a lot of attention in recent years.

Recently, CoCrFeNiTiAlx high-entropy alloys have been evaluated from different ways. Zhang et al. (2009) have examined the effects of aluminum addition on the structures and mechanical properties of the CoCrFeNiTiAlx HEAs. Thus, they have reported the behaviors exhibited by the alloys with the addition of Al. Later, Zhang and Fu (2012) have recorded that Al content shows an

important effect on physical properties of the as-cast and as-annealed alloys. However, we have noticed that the radiation shielding parameters of CoCrFeNiTiAlx alloys have not been investigated. Therefore, we think that it will be significant to remove this deficiency in the literature.

In the present study, we research the photon attenuation parameters such as MAC, LAC, MFP, HVL, ACS, Z_{eff} and N_{eff} of CoCrFeNiTiAlx alloys. For this purpose, we calculate the parameters by using two different softwares which are Phy-X/PSD and EpiXS. Then, we compare all the results with each other, and examine all the results in detail.

2. Material and Methods

The MAC, which defines the interaction possibility between gamma photons and the mass per unit area for a particular medium, can be calculated by the Beer–Lambert formulated as

$$I = I_0 e^{-\mu t} \quad (1)$$

$$\mu_m = \frac{\mu}{\rho} = ln(I_0/I)/\rho t = ln(I_0/I)/t_m \quad (2)$$

where I_0 and I are incident and attenuated photon intensities, ρ is the density of material, μ_m and μ are the MAC and LAC, t_m and t are sample mass thickness and the thickness, respectively. If the sample has different elements, the total MAC for any compound is in the following form (Jackson and Hawkes, 1981)

$$\mu/\rho = \sum_i w_i (\mu/\rho)_i \quad (3)$$

where w_i and $(\mu/\rho)_i$ are the weight fraction and the MAC of the ith constituent element, respectively.

HVL is a thicknesses parameter that is the used to reduce the radiation intensities by one half. MFP is the average distance between two interactions at which a photon travels through the material. The μ is used to obtain the parameters given by

$$HVL = \frac{In(2)}{\mu} \quad (4)$$

$$MFP = \frac{1}{\mu} \quad (5)$$

The ACS, σ_a, for any sample can be calculated using the equation formulated as

$$ACS = \sigma_a = \frac{N}{N_A}(\mu/\rho) \quad (6)$$

where N_A and N are the Avogadro's number and the atomic mass of materials, respectively.

The Z_{eff} of the material can be written as

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \quad (7)$$

where σ_e is electronic cross section.

We can calculate the N_{eff} as follows (Han and Demir 2009)

$$N_{eff=\frac{\mu_m}{\sigma_e}} \quad (8)$$

3. Results and/or Discussion

The CoCrFeNiTiAlx multi-component alloys investigated with this study have been coded as C1, C2, C3, C4 and C5 as-cast case and A1, A2, A3, A4 and A5 as-annealed case according to the percentage of Al element. The chemical composition, density and sample codes of CoCrFeNiTiAlx are shown in Table 1. The radiation attenuation parameters of CoCrFeNiTiAlx multi-component alloys are acquired by Phy-X/PSD and EpiXS softwares in order to make a comparative study. Phy-X/PSD software can calculate the parameters in the energy range of 1 keV - 100 GeV, while EpiXS code can provide those in the energy range of 1 keV - 1 GeV. Our study has been carried out for the values of common energies obtained as a result of the calculations of Phy-X/PSD and EpiXS softwares.

Table 1. Composition, density values and sample codes of CoCrFeNiTiAlx alloys.

Alloy	**As-cast**		**As-annealed**	
	Density (g/cm^3)	**Sample code**	**Density (g/cm^3)**	**Sample code**
$CoCrFeNiTiAl_0$	7.52	C1	7.55	A1
$CoCrFeNiTiAl_{0.5}$	6.67	C2	6.67	A2
$CoCrFeNiTiAl_{1.0}$	6.69	C3	6.71	A3
$CoCrFeNiTiAl_{1.5}$	6.37	C4	6.41	A4
$CoCrFeNiTiAl_{2.0}$	6.12	C5	6.18	A5

In our work the MAC values are calculated by using Phy-X/PSD and EpiXS in the photon energy range between 1 keV - 1 GeV. Change of the MAC values with energy is presented in Figure 1.

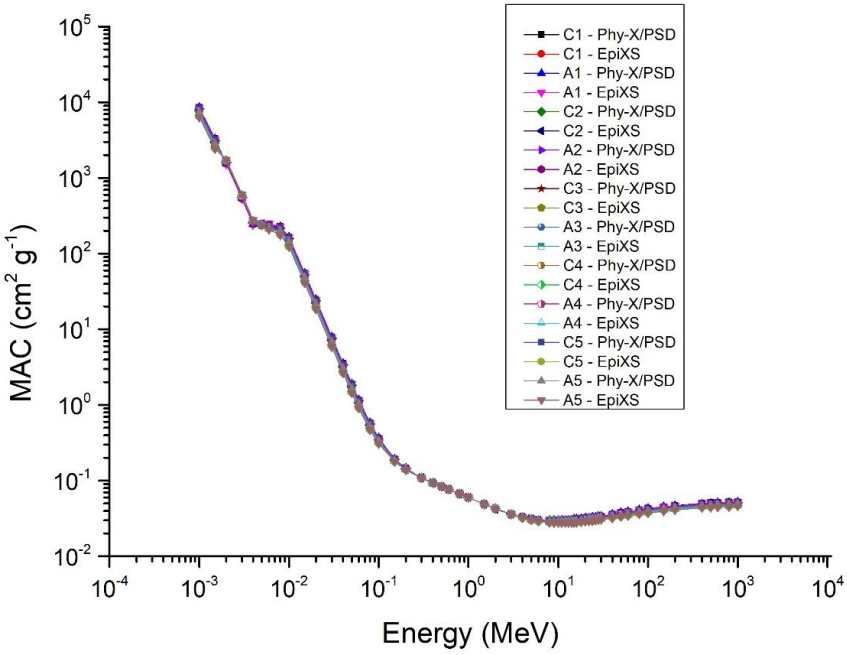

Fig. 1. The variations of MAC values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases.

The variations of the MAC values appear to be similar to each other. It is seen that the MAC values change with both primary photon energies and chemical compositions. It is observed that the MAC values of the investigated CoCrFeNiTiAlx alloys have highest values in the low energy region. The highest MAC values have been calculated for the sample CoCrFeNiTi and Phy-X/PSD code. On the other hand, the lowest MAC values are in the sample CoCrFeNiTiAl2.0. As a result of this, we can say that MAC values decrease with the addition of Al content. Thus, we can conclude that the alloy without Al content has better absorption capacity than the materials with Al.

Then, the LAC values over Phy-X/PSD and EpiXS are calculated, and the variation of the results with photon energies are displayed in Figure 2. It is well known that the LAC values are determined by multiplying the MAC values by density. Therefore, the variations of the LAC values with the energy are similar to the variations of MAC values. Additionally, we can say that the LAC values decrease with the addition of Al content.

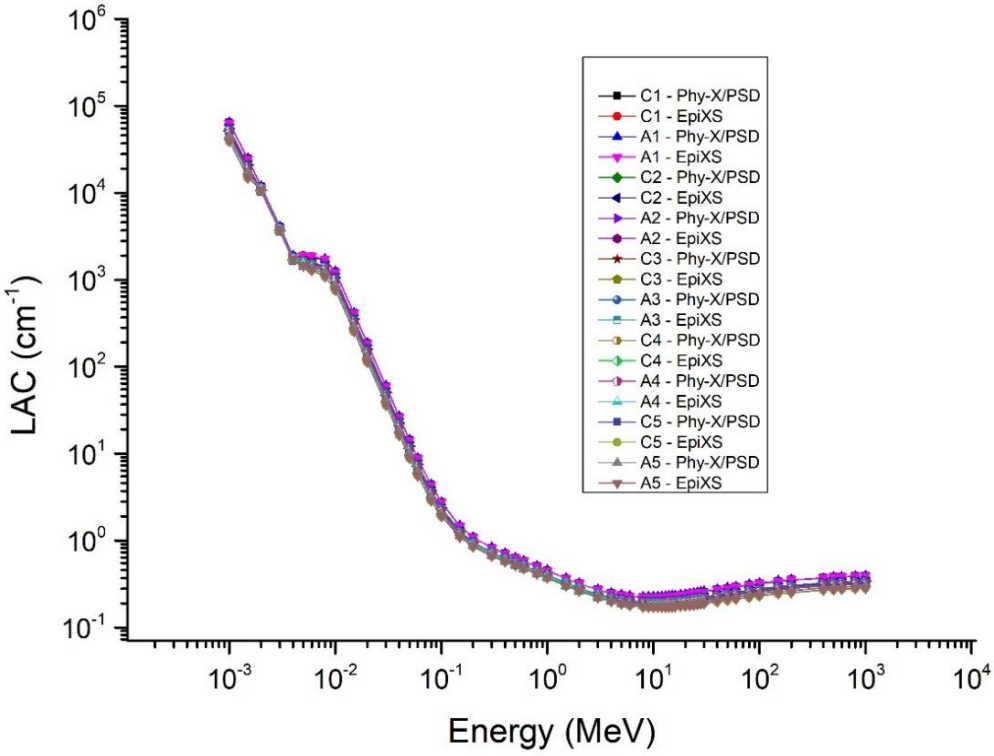

Fig. 2. The changes of LAC values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases.

The MFP and HVL parameters can provide the information about the penetration ability of the radiations in materials. Compton scattering is dominant in the mid-energy region and the absorption probabilities are lower. Therefore, thicker materials for longer MFP values are needed. In this context, the MFP and HVL values are obtained by Phy-X/PSD and EpiXS softwares, and their variations as a function of energy are presented in Figures 3 and 4, respectively. It is founded that both MFP and HVL values are close to zero in the low energy region. Then, the HVL and MFP values shows a sudden increase in the region of middle energy. We can say that the MFP and HVL values increase with the addition of Al content. Thus, we can be say that CoCrFeNiTi has the best shielding potential among the investigated alloys.

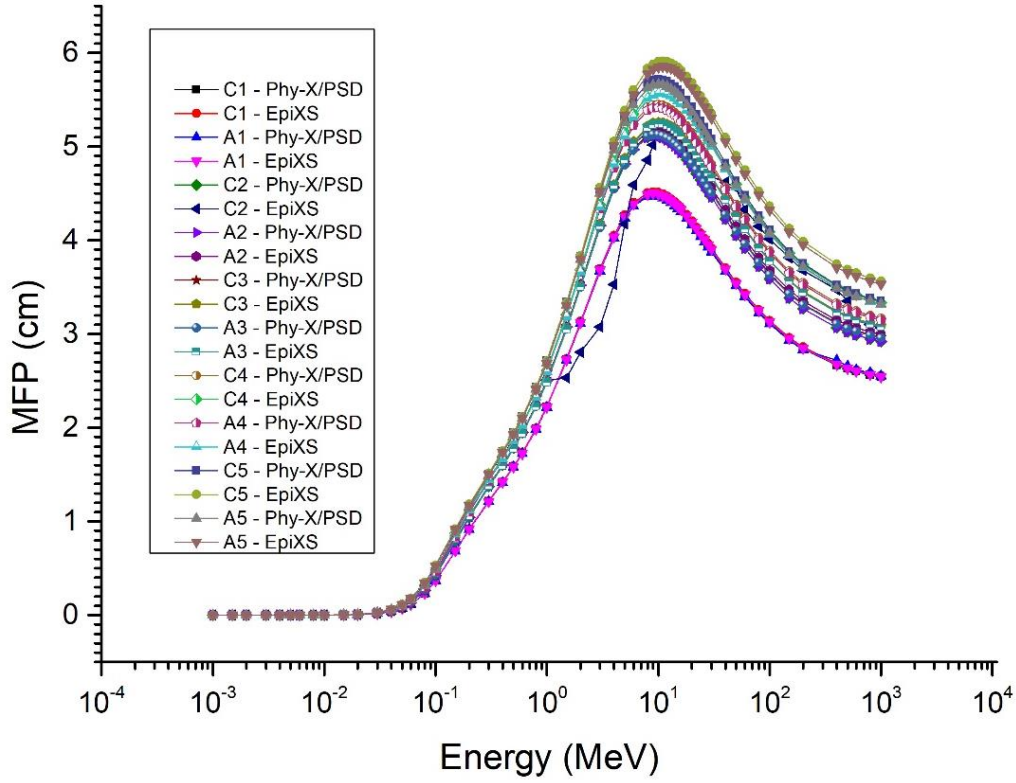

Fig. 3. The variations of MFP values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases.

The ACS values gives the information about the interaction possibility of per atom in a unit volume of any sample. It is assumed that the sample with high ACS value is better material for radiation shielding. In this work, the ACS values are acquired by Phy-X/PSD and EpiXS softwares. Changes of the ACS values with photon energies are presented in Figure 5.

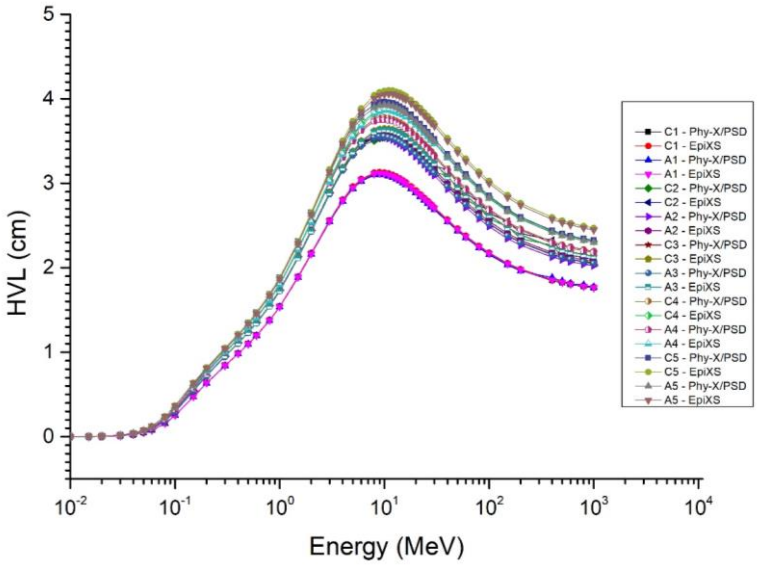

Fig. 4. The variations of HVL values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases.

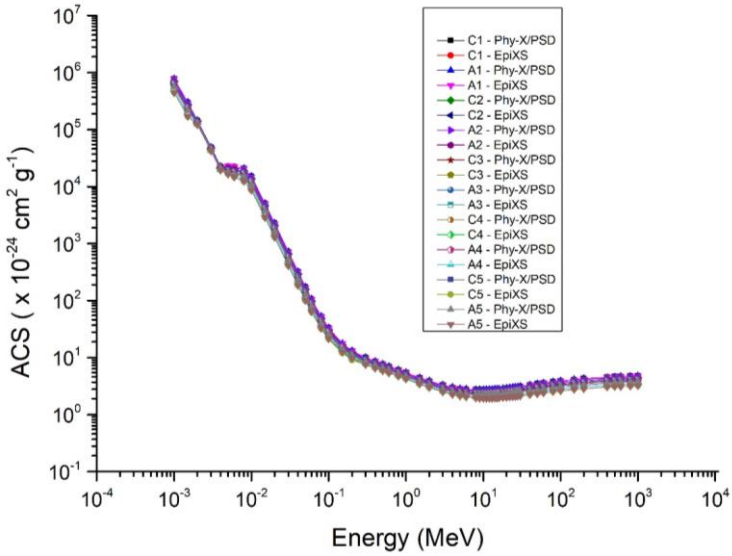

Fig. 5. The variations of ACS values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases.

The ACS values are interconnected the chemical composition of the sample. It is noticed that the ACS values decrease with the addition of Al content. Thus, it can be say that CoCrFeNiTi sample has the best shielding potential among the investigated alloys.

Maximum Z_{eff} values are obtained because of the photoelectric effect at low energy. The larger Z_{eff} causes the interaction between the photons and more free electrons (Wang et al. 2021). In our study, the Zeff values for all the samples are calculated by using Phy-X/PSD and EpiXS softwares, and the results are shown as a function of incident photon energies in Figure 6. By increasing energy, Z_{eff} values are decreased sharply, and then gradually increase and remain constant for high energies. Also, it is seen that the Z_{eff} values decrease with the addition of Al content.

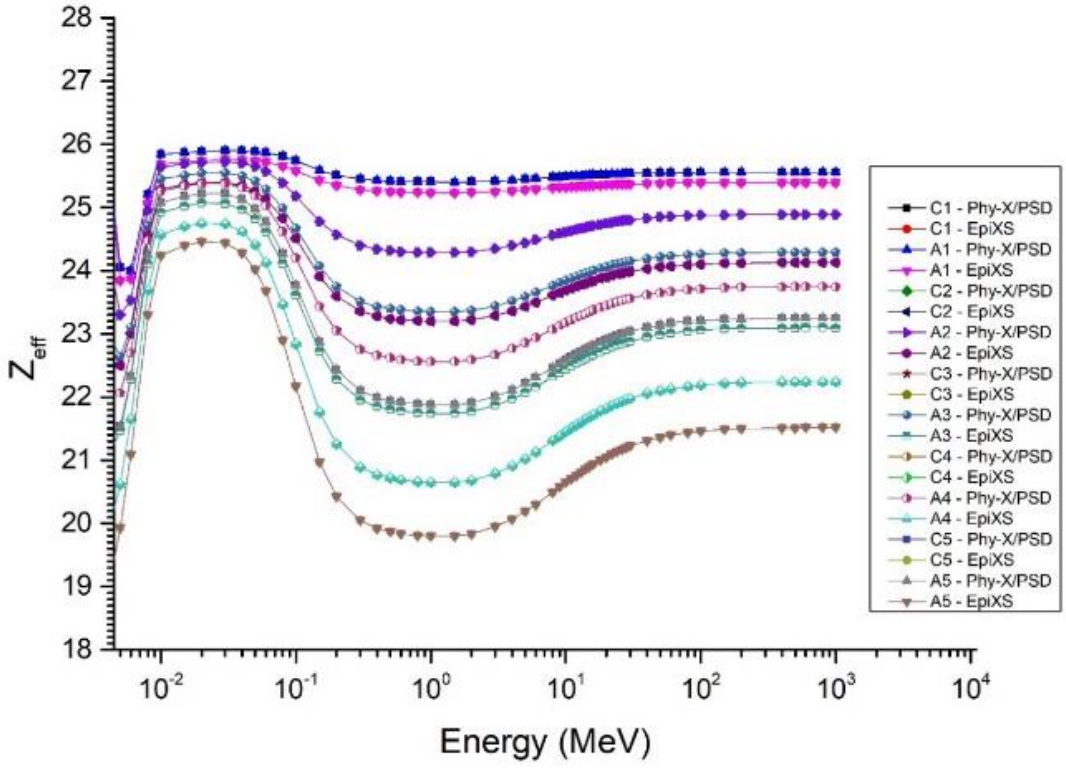

Fig. 6. The variations of Z_{eff} values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases

Finally, the N_{eff} values for all the samples are calculated by using Phy-X/PSD and EpiXS softwares, and the results are shown as a function of incident photon energies in Figure 7. The N_{eff} which describes the effective electron density of the compound depending on the excitatory photon

energy (Alım 2020b) is another of the most important parameters. The N_{eff} values obtained by two codes are in good agreement in mid-energy region. There are deviations in agreement of those in low and high energy regions. As can be seen from Figure 7, the change of the N_{eff} values on the incident photon energies is similar with the change of Z_{eff} values.

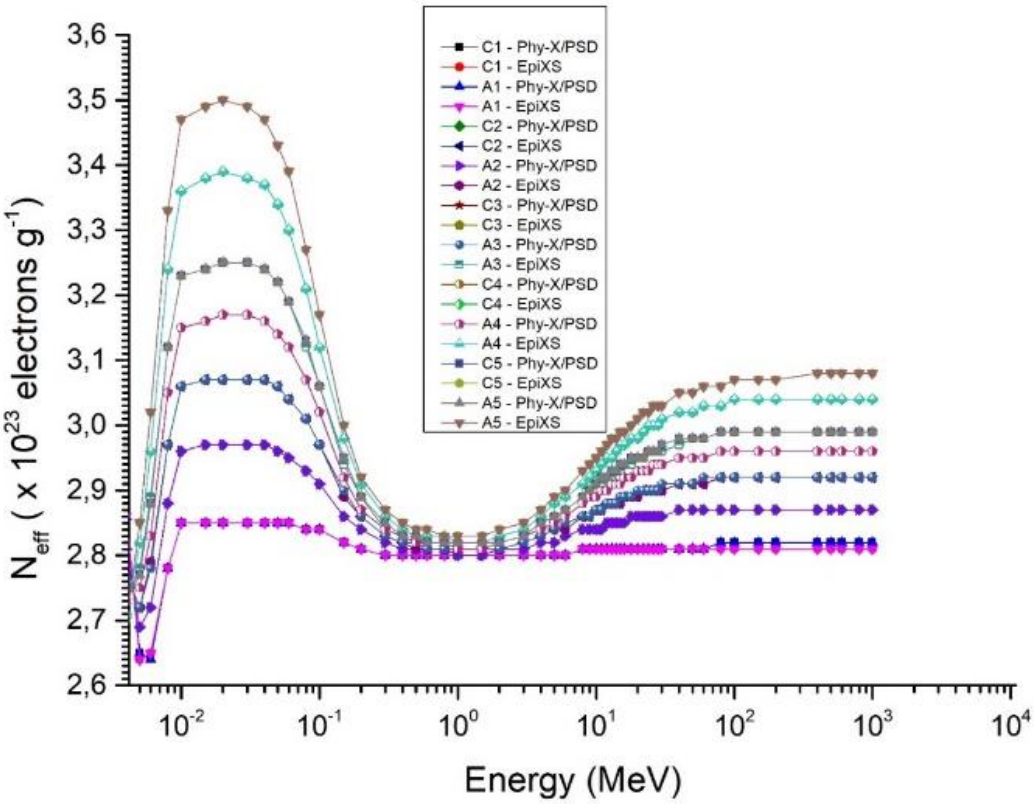

Fig. 7. The variations of N_{eff} values calculated by using Phy-X/PSD and EpiXS for as-cast and as-annealed cases.

4. Conclusion

In this research, we have examined the radiation shielding potential of CoCrFeNiTiAlx multi-component alloys by determination of photon attenuation parameters. With this goal, we have calculated photon attenuation parameters using two softwares called as Phy-X/PSD and EpiXS reported lately. The MAC, LAC, MFP, HVL, ACS, Z_{eff} and N_{eff} changes of CoCrFeNiTiAlx alloys have been given in the energy range of 1 keV – 1 GeV. It has been seen that the absorption capacity decreases with increasing Al element for the evaluated CoCrFeNiTiAlx alloys. Thus, it can be said that CoCrFeNiTi sample has the best shielding potential among the investigated alloys although the results obtained are close to each other. Additionally, we have observed that the radiation shielding results of Phy-X/PSD and EpiXS softwares can show differences according to the as-cast and as-annealing cases.

Conflicts of interest

The authors declare that there are no potential conflicts of interest relevant to this article.

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