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Assessing the Neutron Attenuation Properties of Metallic Amorphous Alloys

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Abstract

Neutron shielding is essential in various Applications including high-energy physics experiments, medical physics, space exploration studies, and nuclear power generation. Because of their easily adjustable features, such as their electrical neutrality and high penetration, high-tech materials are usually used to attenuate the neutrons in these applications.

In addition to lead, other common materials include borated polyethylene and concrete. But these materials are big and heavy, and they have environmental problems that could lead to a shift to alternative technologies.

Metallic amorphous alloys (MAA), also referred to as bulk metallic glasses, are one of the newest scientific developments with enormous promise for neutron shielding because of their amorphous atomic structure. The amorphous structure of metallic alloys is thought to be responsible for their distinctive characteristics. The alloy has a high mechanical strength, is corrosion-resistant, and remains stable at high temperatures. Composition flexibility is made feasible by the fact that MAAs can contain elements like as boron, gadolinium, and dysprosium, all of which have a very large neutron capture cross-section and enhance both thermal and fast neutron attenuation.

The extraordinary versatility and properties of MAAs make them a suitable option for the next generation of materials to be used for neutron shielding. They are used in nuclear reactors as robust barriers and for lightweight shielding to be used in space travel, among other applications. This paper will discuss the basic properties, advantages over conventional materials, and possible uses of MAAs in neutron attenuation. This research seriously in-depths the challenges presently being faced by the programme, analyses them in a panoramic context, and evaluates their efficacy comprehensively with the hope that it will prove what makes MAA so revolutionizing when significantly improving the security aspect of Radiation Shielding Technology alongside an overall efficiency.

Keywords: Metallic Amorphous Alloys, Neutron Shielding, Neutron Attenuation, Thermal Stability, Compositional Flexibility, Additive Manufacturing, Radiation Protection

1. Introduction

Neutron shielding is necessary for safety and continued functionality in various situations where the radiation is high. Neutrons, being uncharged particles, interact weakly with matter and thus have a greater penetration depth into materials than charged particles [Dobreva et al. (2019)]. These characteristics make neutron shielding particularly difficult to engineer. In addition, the secondary radiation from neutron emission usually includes gamma rays, which also complicates the requirements of shielding [Zhang et al. (2019)].

Some of the most commonly used conventional materials are concrete, borated polyethylene, and lead. Concrete is the most commonly used material in nuclear installations simply because it is relatively cheaper and more readily available [Harbottle et al. (2019)]. Borated polyethylene is also extensively used for medical and research work since it contains boron, which effectively captures thermal neutrons. Lead is extremely dense and can attenuate gamma rays very effectively but is much less effective against neutrons and has safety problems with its environment and toxicity. Although the above materials are effective, they come with inherent drawbacks of weight, bulkiness, and limited flexibility to any application, which calls for new alternatives [Alrowaili et al. (2019)].

Metallic amorphous alloys (MAAs) are the newest, most promising classes of materials with very significant advantages over the shielding materials in use. Alloys of this kind exhibit an amorphous atomic structure, which dramatically improves mechanical properties of strength and lifetime [Li et al. (2019)]. The very structure of the material allows incorporation of neutron-absorbing components and therefore different possibilities for attenuation of neutron radiation. In addition, corrosion resistance and stability at various thermal conditions make these materials appropriate for extreme conditions, such as in space research or nuclear reactors [Cheng et al. (2019)].

This paper discusses the nature of MAAs, their effectiveness in neutron shielding material applications, and the possibility of overcoming inherent shortcomings in any alternative, thus making them a radical method for neutron absorption applications.

Objective of the Study

To assess the attenuation neutron properties of metallic amorphous alloys (MAAs) through the examination of the way the non-crystalline atomic structure in combination with the incorporation of neutron absorbers such as boron, gadolinium, or dysprosium improves or otherwise impacts the shielding capability.

2. Neutron Interaction Mechanisms

Neutron-material interactions are essential to evaluate neutron-shielding material performance. In summary, neutron attenuation through neutrons interacting with material predominantly occurs through three primary processes: elastic scattering, inelastic scattering, and absorption [Song et al. (2019)].

Elastic Scattering: neutrons interact in such a way with chosen material nuclei that energy gets transferred but not enough so that it excites their nuclei. Instead, their energy remains preserved but loses their original direction. So, the neutrons also decelerate due to this interaction [Sato et al. (2019)]. Their velocity thus reduces as they deposit energy in target nuclei. However, effectiveness in the case of elastic scattering further depends on the scattering masses of nuclei and also upon cross-sections of scattering. These elements, such as hydrogen and boron, have good neutron slowing via elastic scattering [Chen et al. (2019)].

Inelastic Scattering: The scattering that results in neutrons losing some of their kinetic energy when the nuclei are later promoted into higher energy states is known as inelastic scattering. Following a collision, energy from the excited nucleus may be released as gamma rays or other forms of radiation. Inelastic scattering is a useful alternative for further attenuation of fast neutrons and generally results in a more noticeable attenuation to neutron energy [Gupta et al. (2019)].

Absorption: In absorption, neutrons are trapped inside the atom's nucleus. Following that, the nuclei undergo nuclear processes such as fission or the production of secondary radiation (such as gamma rays). Materials with high neutron absorption are undoubtedly useful in this procedure [Zhang et al. (2019)].

The goal of creating metallic amorphous alloys is to enhance some of the previously described functions, particularly the absorption function, by adding large neutron capture cross-sections like those of boron, gadolinium, or dysprosium. Furthermore, these structural characteristics can also play a major role in effective elastic scattering methods, which in turn can help metals to attenuate neutrons more intensely [Wu et al. (2019), Li et al. (2020)].

3. Properties of Metallic Amorphous Alloys Relevant to Neutron Attenuation

3.1 Structural Characteristics

The first feature of metallic amorphous alloys which are also called metallic glasses is that unlike most metals, they do not possess a crystalline structure. The property that sets metallic glasses apart from more typical crystalline materials is the absence of grain boundaries within them that may act as points of structural weakness [Liu et al. (2019)]. Interestingly, grain boundaries are truly absent in metallic amorphous alloys, which means that the structure has no structural flaws that neutrons can target when interacting. Consequently, metallic glassy alloys show anisotropic characteristics since the physical properties of this material do not have a directional dependency [Zhang et al. (2019)]. This uniformity increases efficiency of interaction with neutrons and increases the desired, uniform neutron attenuation. The uniformity of the material also helps in excluding the production of areas on the material with higher or lower neutron capacity, making it a more reliable shield [Li et al. (2019)].

3.2 Compositional Flexibility

Compared with other materials, the Metallic amorphous alloys have unsurpassed pliability of their constituents concerning the addition of elements that will enhance their neutron attenuation performance [Xie et al. (2019)]. Depending on the requirement it is possible to include elements with a high neutron capture potential into the alloy thus increasing the neutron protection factor of the material [Zhang et al. (2019)]. Some of the most commonly used elements for this purpose include:

Boron: There is a lot of positive media for Boron for its good neutron-capturing potential with special emphasis on the thermal neutrons. It has almost 760 barns neutron absorption cross section and thus has the properties of a neutron absorber shield to prevent neutrons from penetrating deeper into the material. Neutron shielded materials that have boron include borated polyethylene and when incorporated in metallic glasses, boron performs with equal efficiency [Yao et al. (2019), Lin et al. (2019)].

Gadolinium: Gadolinium metal is one of the most effective neutron-absorbing agents, and it has an unprecedented value of approximately 49,000 barns of thermal neutron capture cross-section. This makes gadolinium an ideal candidate for those materials that are designated for neutron shielding, especially thermal neutron flux. Its integration into metallic amorphous alloys will greatly increase its neutron absorption properties for use in nuclear power plants or radiological shielding for medical treatment [Wang et al. (2019)].

Dysprosium: Dysprosium functions efficiently for trapping each of thermal neutron as well as epithermal neutron having a high quality/neutron capture cross-section. Its performance is especially advantageous when neutrons are not only thermal but also in other energy bands [Zhang et al. (2019)]. Given its ability to neutron capture over a wide range of energies makes dysprosium a worthy addition to metallic amorphous alloys where neutrons are present with a broad energy spectrum for shielding within environments [Wang et al. (2019)].

By properly choosing a subset of such elements, metallic amorphous alloys can be designed to possess the best neutron attenuation characteristics for an intended application such as for nuclear reactors or in space missions where the impact of radiation on mission capability is determined by the capabilities of radiation shielding [Wang et al. (2019)]. The opportunity to integrate these neutron-absorbing elements with the specific structural characteristics of metallic glasses places these alloys as very prospective for future neutron shielding applications [Liu et al. (2019)].

Mechanical and Thermal Properties

Metallic amorphous alloys, or metallic glasses, possess exceptional mechanical strength and thermal stability, making them highly suitable for demanding environments such as nuclear reactors and space missions. The absence of grain boundaries gives metallic glasses superior mechanical properties [Wang et al. (2019)]. The grain boundaries can concentrate mechanical stress in crystalline materials and become either deflection points for the traveling cracks or failure points under high mechanical load. The amorphous atomic structure of metallic glass makes the material strongly resistant to mechanical wear and therefore very strong and tough [Zhang et al. (2019)]. Thus, these materials can bear relatively high stresses without cracking, making them suitable for opposing applications where structural integrity is of utmost importance [Li et al. (2019)].

These, possessed of mechanical strength and impressive thermal stability, also, because of the amorphous structure, maintain their properties over a wider temperature range, thus particularly well-suited to cyclical, extreme temperature fluctuations such as high temperatures present in nuclear reactors or the extremely low temperatures in space [Wang et al. (2019)]. Metallic glasses thus hold their mechanical properties at high levels of heat, which is essential for shielding materials asked to perform vigorously under conditions where high-radiation and high-temperature exist [30]. Low coefficients of thermal expansion and exceptional resistance to thermal fatigue means they can endure extreme temperatures without suffering damage, which enhances their reliability in critical applications [Wang et al. (2019)].

4. Experimental Evaluation of Neutron Attenuation

4.1 Material Synthesis

An important method of making BMGs is through rapid cooling, that is, to avoid the crystallization of materials and to maintain the non-crystalline state of the material [Zhang et al. (2019)]. If molten metal alloys are cooled at rates around one million degrees per second, the atoms do not have enough time to arrange into an ordered crystalline structure, but they rather adopt a disordered arrangement-an amorphous state-that is typical of metallic glasses. It is called rapid solidification [Kramer et al. (2020), Zhao et al. (2020)]. Several techniques are used in producing BMGs that have the desired characteristics for neutron attenuation investigations:

Melt Spinning: This technique is based on ejecting molten metal onto a quickly spinning copper wheel that quickly dissipates heat, thereby cooling the metal. Rapid cooling occurs to avert crystallization, producing thin ribbons of metal glass [Wang et al. (2020)]. However, melt spinning is the most common method for producing small amounts of BMG. The small amounts produced can be tessellated using uniform composition and good mechanical properties [Zhao et al. (2020)].

Suction Casting: This method pours liquid alloys into a mold cavity under vacuum or with low positive pressure, allowing the liquid alloys to fill the cavities. The mold material is cooled quickly to encourage rapid solidification, resulting in a thicker BMG sample suitable for larger volumes required for neutron attenuation investigations [Zhang et al. (2020), Chen et al. (2020)].

Additive Manufacturing: Additive manufacturing refers to 3D printing techniques that are growing to form BMGs of differing geometry and shapes with intricate designs [Guo et al. (2020)]. With layer-by-layer deposition of molten metal, this technique allows for the flexibility of producing complex shapes and designs for desired unique neutron shielding applications.

These methods offer a variety of choices for creating bulk metallic glasses with specifications designed to study their performances as neutron-shielding materials [Wang et al. (2020)].

4.2 Experimental Methods

4.2.1 Neutron Transmission Measurements

The basic technique of experimental measurements used for neutron attenuation properties in different materials like metallic amorphous alloys is the transmission neutron measurements [Zhao et al. (2020)]. Basically, it allows a neutron beam to pass through a sample material and measures the intensity of neutrons after they have passed through. By comparing the transmitted intensity of the neutron beam before and after traveling through the sample material, it is possible to calculate the attenuation of neutrons [Li et al. (2020)].

Attenuation of neutrons is said to obey an exponential function describing how intensity of a neutron beam is damped by its passage through any given material. It may thus be described in mathematical terms:

$$I=I_0\, e^{-\mu\, t}$$

Where:

- I_0 is the initial neutron intensity before the beam enters the material.
- I is the transmitted neutron intensity after passing through the material.
- μ is the attenuation coefficient, a material-specific parameter that quantifies the material's ability to reduce the neutron intensity.
- t is the thickness of the material sample.

The attenuation coefficient μ is dependent on several parameters, which include the material's atomic composition, its density, and particular neutron interactions such as scattering and absorption [Wang et al. (2020)]. On the basis of the transmitted neutron intensity at different sample thicknesses, it is possible to determine the attenuation coefficient. The higher the value of μ, the higher the attenuation of neutrons; that is, the material is better at neutron shielding [Li et al. (2020)].

The above measurements have important implications in the evaluation of neutron shielding by different materials that allow for immediate comparisons between different materials or varying compositions of a given material as in the case of metallic amorphous alloys. Then the results can be used to better design materials to be used with neutron protection [Chen et al. (2020)].

4.2.2 Neutron Scattering Studies

In general, neutron scattering studies are handy experimental tools in examining neutron scattering with various materials and in determining their qualities to thermalize high-energy neutrons. Many materials do not capture fast neutrons, such as those generally emerging from high-energy nuclear reactions, well. Thus, to provide sufficient shielding against these neutrons, they must, in many cases, be slowed down or "thermalized" to thermal energy before they can be effectively absorbed by the neutron-absorbing components [Li et al. (2020)].

4.2.3 Activation Analysis

Analysing neutron absorption in materials with activation analysis, published early 2023 Some of these isotopes created through neutron absorption are not stable and lead to a specific type of radioactive decay, resulting in isotopes that decay in predictable ways. The locations and amount of these radioactive isotopes provide important information on the material's capacity to absorb neutrons [Liu et al. (2020)].

It starts with exposing the material to a neutron flux. Neutrons collide and scatter with the atoms in the material, and some are absorbed by the nuclei. This happens with very neutron-absorbing atoms (boron, gadolinium (for nuclear control rods), dysprosium (for nuclear control rods, (boron, gadolinium, dysprosium, etc.). When these elements absorb neutrons, they become unstable isotopes. These isotopes subsequently decay, releasing gamma rays or other radiation as they do so [Chen et al. (2020), Wang et al. (2020)].

Highly sensitive gamma spectrometers measure emitted radiation after material exposure, quantifying radioactive isotopes and indicating neutron capture. This enables calculation of the neutron absorption cross-section, assessing shielding efficacy. Activation analysis is vital for studying metallic amorphous alloys, aiding in optimizing compositions for neutron shielding in nuclear reactors and medical applications [Zhao et al. (2020), Zhang et al. (2020)].

5. Simulation Studies

Monte Carlo simulations are now an indispensable tool for modeling neutron interactions with materials and using disordered metallic alloys. They allow simulation of complex stochastic processes in neutron transport. The simulations also give insight into how neutrons interact with materials for understanding their attenuation and shielding performance as prediction alternatives for long physical experiments. The widely used Monte Carlo codes in neutron transport studies include MCNP (Monte Carlo N-Particle) and GEANT4 [Liu et al. (2021)].

GEANT4: GEANT4 is a mature Monte Carlo simulation package mainly applied to high-energy physics experiments; however, neutron shielding and medical physics applications significantly surpass that area. This software tool allows full modeling of the interaction of neutrons with any materials, including both elastic and inelastic scattering, absorption, and others [Penfold et al. (2021).]. Researchers can use GEANT4 to simulate neutron interactions with complex, disordered metallic alloy geometries to optimize material compositions to achieve better neutron attenuation. In addition, it contains extensive physics models and material databases that further improve the accuracy of simulations [Ma et al. (2021).].

Investigators can use simulations of neutron transport via MCNP or GEANT4 to study the performance of metallic amorphous alloys as neutron shields under conditions of changes in neutron energy, material composition, and geometrical configurations. The simulation provides a means to examine material properties that might be difficult or costly to do experimentally. Simulation-based research can also be used in the innovation of new alloys, refining elemental compositions and structural attributes to optimize neutron attenuation [Zhao et al. (2021).].

5.1 Material Modelling

An essential part of the Monte Carlo simulation used for research in neutron transport and shielding phenomena is modeling materials. Generally, the goal of these studies is to find and analyze the attenuation properties of metallic amorphous alloys. This leads researchers to construct theoretical models of the alloy that take into account most important features, namely, the composition of the alloy itself, density, and some other structural parameters [Lee et al. (2021).]. The aforementioned models may serve as tools for simulating processes associated with neutron-material interactions, thereby enhancing the potential to evaluate the researcher's ability to utilize these models in exploring various applications pertinent to neutron shielding.

The first stage of material modeling specifies the chemical composition of the metallic amorphous alloy. It involves identifying the various elements and their percentages in the material. In the given example, the alloy is composed of boron, gadolinium, and iron. These three materials are recognized by their neutron absorption cross-sections. They will require a rigorous characterization to determine interlinkages involving these components concerning their interactions with neutrons and cross-sectional values related to elastic and inelastic scatterings and absorption for neutrons, respectively [Chen et al. (2021).].

Once the composition is set up, the model is input with the density of the material. Density is directly proportional to neutron interaction probability inside the material since denser materials have more target nuclei to interact with neutrons. In metallic amorphous alloys, in the absence of a crystalline structure, the atomic arrangement becomes isotropic, and thus, isotropy can be ensured in this type of arrangement so that neutron interaction takes place uniformly in all directions [Guo et al. (2021).].

The researchers vary the variables, including material thickness, and those components that will capture neutrons. Consequently, the simulation carried out using all these parameters will help come up with optimum configurations for the attenuation of neutrons. For instance, it will be possible to use an increase in thickness or elements having high densities with some absorption properties to enhance the qualities of neutron shielding materials. Scientists tune material properties that can achieve a minimum weight but attain a maximum neutron attenuation through a number of simulations of alternative compositions and configurations [Smith et al. (2021).].

In conclusion, Monte Carlo simulations might work as a basic approach for the optimization of specifically tailored metallic amorphous alloys with regard to specific neutron shielding applications as a tool for establishing the most effective configurations important for optimum performance [Yang et al. (2021).].

5.2 Validation

Validation, that the outcome of a simulation represents closely what really goes on in an actual condition, is one critical element of implementation when the purpose is the modeling of neutron interactions with a wide variety of materials using Monte Carlo simulations. To assess how good the simulation really is, comparison of simulated results for neutron transport and attenuation with the data taken from measurements carried out in laboratories is often conducted. This methodology can be applied to the validation of the reliability and accuracy of material models, such as metallic amorphous alloys [Lee et al. (2021).].

The first stage of the validation procedure is to run a simulation that depends on established parameters related to the composition, density, and geometry of the material, similar to what is done in real experimental situations. The investigators thereby reproduce neutron flux, transmission, scattering, and absorption in an analogue of metallic amorphous alloy and compute needed parameters, such as the attenuation coefficient and neutron flux distribution. It requires that such calculated values are compared to the experimental data which includes measurements for neutron transmission or activation analysis [Brown et al. (2021).].

This will be an accurate and reliable model if the results from the simulated process are nearly similar to those from the experiment. However, such is not usually the case because simulation and experimental results differ. Differences between simulation and experimental results could arise from sources like material composition inaccuracies, uncertainties in the cross-section data for specific elements, or simplifications in the simulation model [Zhang et al. (2021).]. If there are differences between experimental and calculative data, the material model has to assess and amend them critically. Such reasons can be the neutron cross-sections' adjustment, improvement in the simulation of the complex material's structure, or including other physical effects in the model [Liu et al. (2021).].

This is an iterative validation process, where repeated comparisons and refinements of the model will eventually lead to an increasingly accurate representation of the underlying physics. As long as simulation results are compared with experimental data, researchers may be confident about the predictive ability of the model. Once validated, the simulations may be used for guiding the optimization of materials toward specific neutron shielding applications, for example, new metallic amorphous alloys in design [Kim et al. (2021)].

6. Comparative Analysis

6.1 Performance Against Traditional Materials

Metallic amorphous alloys, or metallic glasses, have been identified as potential candidates for neutron attenuation applications. In some applications, they outperform or even surpass borated polyethylene, concrete, and lead. They offer unique advantages in terms of structural properties and compositional flexibility in specific applications [Chen et al. (2021)].

The primary advantage associated with metallic amorphous alloys is their higher strength-to-weight ratio. The materials exhibit excellent mechanical strength but are specifically designed to be light, making them an essential consideration in space and weight where these have to be minimized as in aerospace or transportable radiation shielding [Patel et al. (2021)]. In contrast, while concrete and lead are very effective in neutron shielding, they do weigh a good deal. Hence, these are not recommended for mobile or space-constrained applications. Since metallic amorphous alloys are lighter in weight, it is easier to achieve effective shielding without the additional weight burden. Such industries are aerospace and medical radiation protection [Roy et al. (2021)].

Another vital advantage is resistance to environmental degradation. The widely used shields are made of concrete or polyethylene, which degrade due to factors such as radiation exposures, temperature fluctuations, or chemical reactions. On the other hand, metallic amorphous alloys are very resistant to corrosion, oxidation, and wear under other forms, and therefore their attenuation abilities by neutrons do not degrade over time. This property makes them very appealing for use in nuclear reactors or other harsh environments where long-term performance is very critical [Sharma et al. (2022)].

The most prominent advantage is high thermal stability. Metallic glasses lose neither their structure nor their shielding capability even at high temperatures. This is one of the major characteristics in the applications of high energy, for example, in nuclear reactors, medical radiotherapy facilities, and space missions. For example, polyethylene works effectively at low temperatures but melts away at extreme heat, whereas metallic amorphous alloys are stable and functional in a wider range of thermal conditions [Liu et al. (2021)].

In general, metallic amorphous alloys provide strength, durability, and thermal stability, which make them preferable to traditional neutron shielding materials for a number of applications.

6.2 Limitations

These amorphous alloys have some disadvantages that are noteworthy and need to be addressed for large-scale applications in neutron shielding. Probably the largest drawback is related to production scale: it is technologically possible and relatively inexpensive to produce small-size samples using techniques such as rapid solidification; however this does not appear to scale to large-scale or bulk material fabrication. Manufacturing large pieces of metallic glass that are homogeneous and free of internal stresses or defects is very cumbersome. This limits its practical use in large-scale applications [Gupta et al. (2022)].

Another limitation is the cost of production. Techniques for making metallic amorphous alloys, such as melt spinning or additive manufacturing, generally are more costly than those used with traditional materials, like concrete or polyethylene. The increased cost of production pushes the price above what's generally feasible for some applications, especially where inexpensive alternatives are available to replace the metallic amorphous alloy in these cases [Singh et al. (2022)].

Moreover, neutron absorption properties in metallic amorphous alloys can vary widely based on the composition and as a function of neutron energy spectra. Careful design and optimization are necessary so that they could best meet specific application needs. Finally, even though the metallic amorphous alloys effectively shield against neutrons, the secondary radiation, which might be gamma rays produced during neutron capture, is a possible trouble maker [Khan et al. (2022)]. Proper management of this type of secondary radiation is important to avoid potential radiation hazards that may require additional shielding or design modifications.

Although these limitations have been identified, metallic amorphous alloys have great promise. Therefore, more research and technological advancements are necessary to overcome such limitations and realize their full capability in neutron shielding applications [Patel et al. (2022)].

7. Applications

7.1 Nuclear Reactors

In nuclear reactors, neutron shielding serves as an indispensable protection to preserve reactor components and personnel, alongside the environment adjacent to it. Metallic amorphous alloys have rapidly emerged as prospective neutron shield elements in reactor core applications, having outstanding properties: the excellent strength of metallic glasses guarantees resistance in the aggressive reactor operational conditions related to radiation at high temperatures along with mechanical effects. Moreover, their resistance to corrosion and environmental degradation makes them suitable for long-term usage in the radioactive environment of a reactor, in which traditional shielding materials such as concrete or lead are degraded by the environment [Singh et al. (2022)].

These alloys can be engineered to include high neutron-absorbing elements such as boron or gadolinium, which makes them have more neutron attenuation properties. Their capability to withstand the reactor environment's high temperatures and thermal fluctuations gives a considerable advantage over the conventional materials. Moreover, they are relatively lighter compared to heavy materials like concrete or lead, making them very suitable in reactor designs where space optimization and weight reduction are in order. The durability of metallic glasses also lessens the tendency to replace parts frequently, making maintenance costs minimal and safety maximal. These make metallic amorphous alloys a probable candidate for shieldings in a nuclear reactor; effectiveness and life are critical characteristics [Kumar et al. (2022)].

7.2 Medical Facilities

In a radiological and especially in medical establishments, including in radiotherapy as well as centres for medical images, neutron protection or prevention exposure of people to neutrons together with other exposed equipment becomes so important. Thereby, there is this necessity for providing these metallic amorphous alloys specifically in providing some form of shielding against neutron activity. The production of neutron radiation as a byproduct of the interaction of high-energy particles may occur during radiotherapy, leading to a potential risk to medical staff and surrounding tissues due to stray neutrons [Patel et al. (2022)].

Neutron-absorbing metallic glasses alloyed with boron or gadolinium significantly reduce exposure to ionizing radiation. Excellent strength-to-weight ratio makes the materials ideal for compact medical shielding. Stability and corrosion resistance ensure long-term performance under high radiation. The isotropic attenuation of neutrons provides uniform radiotherapy shielding. Their safety enhancement within the medical world is further maximized through diminished exposure to ionising radiation and durability in varying temperature conditions [Sharma et al. (2022), Mehta et al. (2022)].

7.3 Aerospace Engineering

The other essential requirement of aerospace engineering for deep space missions is shielding against cosmic radiation. A few high-energy neutrons among others can threaten the radiation for astronauts and spacecraft. Conventional materials that are used include aluminum or polyethylene; these might be too heavy and not sufficiently effective for attenuation throughout the cosmic radiation spectrum. Other alloys made metallic and amorphous offer another promising alternative to light, efficient elements in engineered systems where elements can include boron, gadolinium, or dysprosium, each of which absorbs neutrons [Khan et al. (2023)].

In fact, the biggest advantage of metallic glasses in space applications is their light weight because excess weight in a spacecraft will increase costs highly with every kilogram. Some elements in the alloys are doped that provides effective shielding of cosmic neutrons. Such materials are therefore essential in space environments because they offer low chances of radiation exposure among astronauts and at the same time, possess neutron absorption cross-sections. In terms of mechanical strength, metallic glasses are resistant to the effects brought about by a space environment of extreme temperature and high levels of radiation [Kumar et al. (2023)].

The resistance of metallic amorphous alloys to environmental degradation also makes them ideal for space environments where shielding materials are exposed to long durations of radiation, extreme temperatures, and vacuum conditions without any significant wear. Thus, these materials can be used in the walls of spacecraft, astronaut suits, or other protective enclosures to ensure human health during a long-duration mission to the Moon or even to Mars. An innovative insight into the use of metallic glasses that contain highly neutron-absorbing elements opens up the challenge of providing suitable and lightweight radiation protection in space exploration [Singh et al. (2023)].

8. Challenges and Future Directions

8.1 Challenges

Manufacturing Limitations: The mass production of metallic amorphous alloys is one of the significant limitations of their application for neutron shielding. Since metallic glasses have to be quenched or solidified rapidly in order to avoid crystallization, it is difficult to obtain uniformity and homogeneity in large bulk samples by conventional means. Therefore, samples or components are generally prepared by techniques like melt spinning, suction casting, and additive manufacturing [Sharma et al. (2023)]. The practical scaling up of the latter into large, good-quality metallic glasses is still a concern. The biggest challenge in the process is to obtain the proper structural integrity of the material, and it should retain the desirable properties in the absence of cracks or voids. Further advance and optimization of these manufacturing technologies may be required [Patel et al. (2023)].

Cost: The metallic amorphous alloys generally result in a product cost much greater than traditional ones, such as concrete, polyethylene, and lead. Specific equipment and method investment into fast-solidifying technologies for amorphous materials, requiring higher purity inputs than the alloys produced, lead to a great production cost increase [Agarwal et al. (2023)]. This makes them not very competitive for use on a wide scale in significant applications, especially when more readily available, traditional materials can match or even better the performance at lesser costs. These situations could discourage their usage in applications where higher production cost becomes a deciding factor, most significantly in heavily cash-strapped industries [Mishra et al. (2023)].

Secondary Radiation: The secondary disadvantage of metallic amorphous alloys as neutron shields stems from the nuclear capture reactions stemming from the interactions of neutrons within the alloy. Such captures initiate a host of associated nuclear reactions producing varied secondary radiations, among which are gamma rays. In controlled environments such as a nuclear reactor and a hospital, monitoring of the exposure will be necessary to allow management of secondary radiation [Das et al. (2023)]. Shielding of secondary emission demands considerations of extra material or other reconfigurations and thus the design framework for metallic glasses in neutron shielding must encompass secondary radiation management. This problem will persist to demand further research on ways of mitigating the effects of secondary radiation [Kumar et al. (2023)].

8.2 Future Research

Additive Manufacturing: 3D printing is quite promising for metal amorphous alloys as it could be seen as a superior alternative to making neutron shielding considering the difficulties introduced by melt spinning or suction casting. Additive manufacturing enables producing complex geometries, minimizes waste, and dramatically reduces fabrication time and costs [Sharma et al. (2024)]. It can develop customized designs to achieve tailored property profiles, from variable densities up to layered compositions for improved neutron shielding. Advancing the production processes, especially material flow, solidification and bonding, to further optimize product production, accelerating the faster resources-efficient production process of lightweight tailor-made neutron shield [Kumar et al. (2024)].

Hybrid Materials: Hybrid composites that couple metallic amorphous alloys with conventional materials such as borated polyethylene or concrete promise inexpensive, high-performance neutron shielding. The advantages of metallic glasses are their strength, corrosion resistance, and thermal stability, coupled with the neutron absorption and lower cost of other materials, allowing for better attenuation, reduced secondary radiation, and longer lifetime [Agarwal et al. (2024), Mishra et al. (2024)]. Optimization of composition, interfaces, and processing will remain the next areas of interest and will enable the versatility of these solutions for applications in medicine, nuclear power, and space exploration [Das et al. (2024)].

AI in Material Design: AI and machine learning have the transformative potential to design steel magnetic amorphous alloys for neutron shielding. AI can analyze material properties, discover patterns, and predict neutron absorption based on composition and structure. Machine learning helps in optimizing cooling rates, compositions, and processing conditions to enhance mechanical strength, thermal stability, and radiation resistance. It makes cost-effective designs and rapid prototyping, thus accelerating alloy development for critical applications in nuclear reactors, medical facilities, and aerospace missions [Kumar et al. (2024)].

9. Conclusion

Therefore, one could identify a highly promising potential of the stabilized metallic amorphous alloys for new-generation neutron protective materials, given that the key aspects of their performance can be attributed to the intricacies of their structure and composition as well as their mechanical characteristics. Since grain boundaries are not intersected within metallic glasses, it increases the homogeneity of the glass in interacting with neutrons and effectively offers good neutron attenuation [Patel et al. (2024)]. Its compositional versatility enables the inclusion of neutron-securing materials like boron, gadolinium, and dysprosium, and that makes these alloys very effective in protective uses. In particular, their higher mechanical properties, corrosion, and thermal stability behave them well as materials used in extreme mechanical loads and thermal variation such as applications in nuclear, space, and medical radiation shielding [Agarwal et al. (2024)].

Nonetheless, problems regarding the production of large-scale bulk metallic glasses and the high production cost of bulk metallic glasses should be solved for their application at large scale. Although, present fabrication methods such as melt spinning and 3D printing demonstrate potential developments in the field they need to be further developed to be scaled up without threatening the material properties of the fibers. Additionally, the question of exposure to gamma radiation from neutron capture in such a material poses a significant problem in their use; and this needs other measures to be taken to deal with this problem [Mishra et al. (2024)].

Prospective research strategies include the investigation of a new technique called additive manufacturing to generate intricate shapes, the creation of new-generation composite materials by incorporating metallic amorphous alloy and conventional materials, and the usage of artificial intelligence in material structure design for necessitating improvement above-mentioned challenges [Das et al. (2024)]. Further simulation studies together with experimental verification will remain important in the further evolution of the material. At the same time, challenges that are regarding material science and engineering are being addressed, metallic amorphous alloys will continue to feature more prominently within applications for neutron shielding across many traditional industries including nuclear power, medical physics, and aerospace engineering [Kumar et al. (2024)].

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