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Metallic glasses — Versatile radiation-tolerant materials for nuclear fusion applications☆

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ABSTRACT

Nuclear fusion (NF) imposes unprecedented requirements on materials involved. Metallic glasses (MGs) offer an impressive set of properties that hold promise to overcome related challenges. These properties range from high corrosion resistance over high mechanical strength to high radiation tolerance including possible self-healing of irradiation-induced structural changes. Their high compositional flexibility allows MGs to be designed for optimal use in various areas of NF devices. Here we provide an introduction as to how these unique properties and related manufacturing processes can be exploited for a multitude of applications in NF. An outline of a development roadmap to expedite efforts in this direction is given.

1. Introduction

Metallic glasses (MGs) exhibit a set of outstanding properties directly arising from their liquid-like *amorphous atomic structure*. These properties are often superior to those of their crystalline counterparts with similar composition [1–3]. A growing number of fields already benefit from the application of MGs [4–9]. Many of their properties make MGs also suitable for the extreme conditions encountered in future nuclear-fusion (NF) devices. Early irradiation studies on these materials date back as far as five decades [10]. The notion that the intrinsic disorder of the amorphous structure might enhance resistance to irradiation by projectiles such as neutrons or ions was also stated early on [11,12]. With NF coming closer to deployment and related materials challenges becoming more and more evident, renewed interest in MGs as important candidates for application in this field can be observed [13–16]. This is also supported by the strongly increased critical casting sizes of MGs since the first irradiation studies [1]. Nevertheless, studies usually only consider the radiation response of existing MG alloys without addressing dedicated design of compositions taking into account the special requirements of NF like transmutation and activation.

Additionally, harnessing the benefits, including the unique manufacturing pathways, of MGs for the wide variety of applications in NF, which are not immediately affected by the harsh conditions, has also not been addressed so far. Such applications include maintenance robotics, hydrogen isotope separation or protection of surfaces coming in contact with molten salts or liquid Li and its alloys.

Here, after briefly providing some background on MGs and their manufacture, we highlight possible use cases of MGs in NF and suggest the focussed design of MGs tailored to the unique needs in NF to be guided by a development roadmap.

2. Background

MGs with practical relevance are usually multi-component alloys with high diversity in atomic sizes [17–19]. On the one hand, this causes the amorphous atomic structure to be “jammed” with the absence of individual atom-sized vacancies and other “weak points” like slip planes, dislocations and grain boundaries known from the crystalline case [1] (cf. lower inset of Fig. 1). In their place, so-called free volume as “delocalised defects” can exist in the amorphous structure which is important for understanding many aspects of MGs including their plasticity, processability and response to irradiation [1,20,21].

On the other hand, the multi-component nature enables a tremendous compositional flexibility of MGs and opens a vast design space for adapting them to different environments and applications [22], including those specific to NF, e.g., requiring high-shielding but low-activation behaviour. It also helps to accommodate in-operando changes of compositions as consequence of transmutation without strongly affecting the atomic structure and related structure–property relationships. The multi-component nature of MGs is a trait shared with high-entropy alloys (HEAs). It was shown that HEAs with properties relevant for NF, especially high radiation tolerance, can be prepared as thin film MGs [15,23–26].

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The jammed amorphous structure prevents atoms to move readily for plastic deformation to occur. Mechanical energy is predominantly stored elastically in the inter-atomic bonds. As a consequence, MGs exhibit several unique properties like mechanical strengths being about three times as high as in crystalline counterparts with same Young's modulus and elastic elongation limits of around 2%, again about three times as high as of comparable crystalline counterparts, as well as high fracture toughness [1–3,27]. Plastic deformation of MGs is mainly driven by the formation of shear bands [28].

The absence of grains and grain boundaries leads to very smooth surfaces of MGs (Figs. 1 (upper inset) and 2a) as well as high corrosion and oxidation resistance, high hardness, high scratch resistance and high wear resistance [1,29,30]. It is worth noting that not all compositions and various families of MGs exhibit all these properties to the same extent. Often it is a combination of these outstanding properties that make MGs uniquely suitable for many applications. Depending on the intended purpose, selection or dedicated design of appropriate alloy compositions will be necessary. Particularly relevant for NF, high radiation tolerance as well as indications of self-healing of irradiation-induced structural changes have been reported [13,21,31,32]. These properties are strongly related to the mentioned free volume and its temperature dependence [21,33,34]. Free volume is also related to the favourable hydrogen retention and embrittlement behaviour of MGs compared to crystalline counterparts [21,35] as well as higher resistance against hydrogen or helium bubble formation due to the lack of traps like dislocations and grain boundaries present in crystalline materials [21,33,36–39].

3. Metallic glass manufacture

Most commonly, MG parts are manufactured by cooling a metallic melt rapidly enough that crystallisation is avoided and the amorphous atomic structure of the liquid is retained during solidification. This kind of solidification, called vitrification, takes place at the so-called glass-transition temperature T_g which is usually several hundred K lower than the liquidus temperature T_l (and the melting temperature T_m) of the alloy (Fig. 1, blue path).

Between T_l and T_g, the alloy is said to be in the undercooled (or supercooled) liquid (UCL) state. This high degree of undercooling does not only cause the density of the UCL (and the forming MG) to approach that of the crystallised material of the same composition (Fig. 1, red path) but also leads to only a very small volume change around T_g during vitrification (Fig. 1). The latter can also be understood by the very similar atomic structures of the MG and that of the UCL close to T_g [41]. An alloy's propensity to vitrify is called glass-forming ability (GFA) and is expressed by the maximal dimensions (usually given as diameter or thickness t_{max}) the material can be cast in with homogeneously glassy structure or by a critical cooling rate necessary to reach this state. The aforementioned jammed atomic structure resulting from the multi-component nature of MG-forming alloys and the high diversity in atomic sizes also impedes the diffusion of atoms in the UCL state leading to increased GFA. This is commonly referred to as "confusion principle" [18,19] and is reflected in the first two of Inoue's three empirical rules for enhanced GFA [17,42]. The third refers to highly negative values of the heats of mixing between pairs of the constituting elements reflecting strong local chemical bonding between them. This decreases atomic diffusivity (increases viscosity) in the UCL state impeding atoms from finding their energetically preferred positions in a crystalline structure during cooling/casting. Various other factors affect GFA as well [1,42–44].

Vitrification can be achieved by a variety of techniques including tilt casting, suction casting, die casting or centrifugal casting into, for example, water-cooled Cu moulds [1] (Figs. 2b, c). The small solidification shrinkage during vitrification (Fig. 1) enables near net-shaped casting of MG parts with various shapes and sizes as well as high precision (Figs. 2b, d, e). Melt spinning, planar-flow casting or splat quenching are other techniques to create MGs starting in the liquid phase [1]. Possible size restrictions due to insufficient GFA of alloy compositions can be alleviated by additive manufacturing (AM) of MGs which is currently the subject of intensive research across different alloy families [45–55] (cf. Fig. 2m).

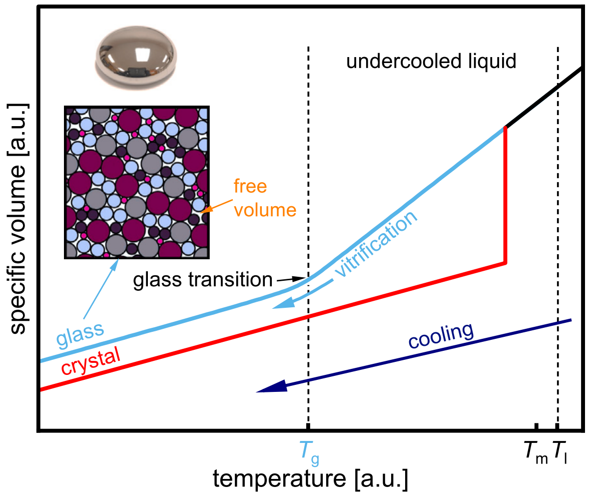

Fig. 1. Schematic temperature dependence of the specific volume of a model alloy quenched from the (equilibrium) liquid phase at high temperature (above the liquidus temperature T_l). Depending on the cooling rate, the (undercooled) liquid can either crystallise (in the example slightly below the melting temperature T_m, red path) or vitrify at the glass transition temperature T_g (blue path). The specific volumes of crystal and glass at low temperature are very similar. The insets show a photograph of a typical as-cast (bulk) MG ingot [40] and a sketch of a 2-dimensional five-component model glass illustrating the multi-component nature of MGs with a high diversity of atomic sizes causing their jammed structure. Distributed free volume is highlighted as well (orange arrow). Both are responsible for many of the unique properties of MGs.

By heating an MG above T_g the material re-enters the UCL state with a highly viscous metallic liquid to be present again. Both, this transformation (on heating) and vitrification (on cooling) are summarised under the term *glass transition*. Shaping MGs via the UCL state after heating them above T_g is another way of circumventing the size limitations [1,56]. This includes thermoplastic forming (e.g. moulding, rolling, extrusion) [56], electromagnetic pulsing [57], imprinting on various length scales [56], injection moulding [58] or, very much similar to oxide glasses, blow moulding [59]. This allows for unique and completely new ways of net-shaping of metallic alloys and the production of parts with complex geometries and very fine details combined with the other outstanding properties of MGs discussed above. It also enables welding of MGs and their use as filler for brazing other (including crystalline) materials [60–64]. Important in this respect, as well as for AM, is a wide UCL region $\Delta T_X = T_X - T_g$, where T_X is the temperature above which the material assumes a crystalline structure followed by the loss of the unique features of the glassy state.

By adopting a very general definition of glass, i.e. being a solid with amorphous atomic structure [41], MGs cannot only be made by methods starting from or involving the liquid phase but also by a wide variety of other techniques including mechanical alloying, sputtering, flash evaporation, electrodeposition, thermal spraying, ion-beam mixing of multi-layers or amorphisation by irradiation of crystalline precursors [1,65–69]. The latter having direct relevance for NF environments. Fig. 2 gives an overview of MG parts made or shaped by various techniques.

4. Radiation response of metallic glasses

Although the investigation of the radiation response of MGs has a long history, it is not explored in as much detail as for crystalline

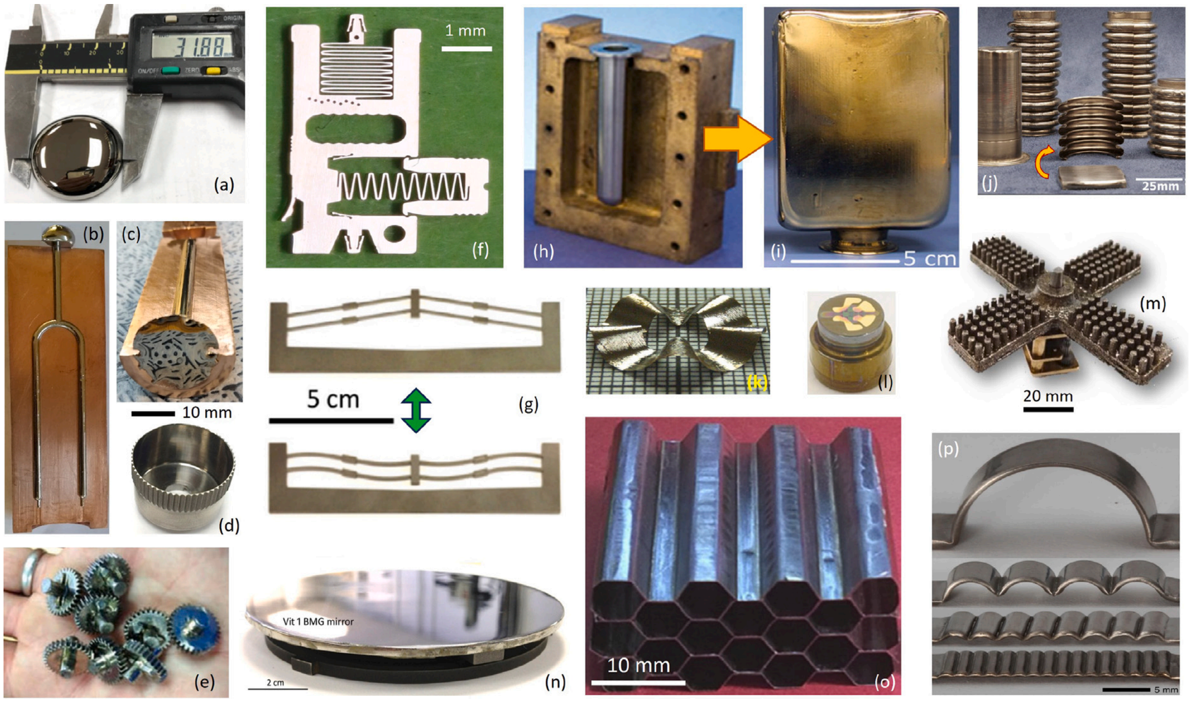

Fig. 2. Examples of MG parts manufactured by different techniques for various applications. (a) As-solidified MG ingot (Cu-based) illustrating the typical smooth surfaces of MGs [70], (b) and (c) suction cast MG parts (Zr-based) inside Cu moulds (Cranfield University), (d) flexsplines for a strain wave gear, as used in robotics, cast to near net shape (Zr-based) [71], (e) near net-shape cast MG gears for use in lubrication-free mechanisms (Ti-based) [72], (f) fully-functional MG MEMS device (accelerometer) moulded in a single processing step [73], (g) two states of a compliant mechanism (Zr-based) [58], (h) and (i) blow-moulded shapes (Zr-based) [74], (j) MG parts obtained by stretch blow moulding of a flat sheet-like feedstock (Zr-based) [75], (k) novel wave springs made from a planar-flow cast MG foil (Fe-based) [76], (l) pressure sensor with MG diaphragm (Zr-based) [1], (m) MG structure (Zr-based) made by AM (powder bed) [46], (n) MG mirror (Zr-based, Vitreloy 1) [58], (o) honeycomb-like structure made by joining thermoplastically formed MG sheets [77], (p) MG strip (Zr-based) shaped by electromagnetic pulsing [57].

metals. Nevertheless, the response of a variety of MGs to a range of different types of projectiles, including photons, electrons, neutrons, hydrogen (protons), helium (α particles) and heavier ions with various kinetic energies, fluences and fluxes has been examined [13,78–82]. Heavy ions are often used as proxies to emulate the effects of neutron irradiation [13,14,33,38,83–86]. Generally, a high radiation tolerance of MGs has been found with effects on structure strongly depending on the particular compositions and conditions [13,14,16]. This includes indications of self-healing of irradiation-induced structural changes in MGs [13,21,31,32]. The beneficial radiation response of MGs in conjunction with their other unique capabilities could enable numerous applications impossible for their crystalline counterparts [16]. Studies also include the (undesired) irradiation-induced amorphisation of monolithic crystalline materials as well as the (desired) creation of MGs by ion-beam mixing of layered crystalline precursors, for instance, to alloy elements with strongly positive heats of mixing commonly unfavoured by Inoue's rules [17,87,88].

Effects on structure have been investigated at several length scales (from changes of the atomic order [89,90] to macroscopic effects like blistering [91]) by various methods (including diffraction techniques [92], directly by microscopy [93], positron annihilation [94] or by proxies including Mößbauer spectroscopy [95,96] and magnetic properties [97] or electrical resistance [98,99]). However, systematic studies comparing many different MG compositions and their irradiation responses under a common protocol as function of projectile, kinetic energy, temperatures, fluence, etc. are missing so far.

Simulating the irradiation behaviour of MGs yields important complementary insights, especially into aspects that cannot be directly accessed experimentally. Although their validity has strongly increased with increasing computational capabilities over the last decades, related studies date back to almost the same time as the first experimental irradiation studies on MGs [100]. Interesting results on collision cascades and sub-cascades could be obtained showing localised melting followed by re-vitrification under extremely high local cooling rates in super-quenched zones causing increased free volume and void-free swelling [21,101–103]. It needs to be noted that the kinetic energy of D-T-fusion neutrons (14.1 MeV) and many of the high-energy heavy ion projectiles used in several experimental studies exceeds kinetic energies of primary knock-on atoms (PKAs) hitherto simulated by far.

5. Metallic glasses in nuclear fusion

Based on the observed high radiation tolerance of MGs [31,32,84, 104–107], several authors recognised NF as prospective application early on even though compositions available at that time did not allow for bulk-sized parts or contained high amounts of elements strongly prone to activation [12,100,108,109]. Following advances since then, their promising high tolerance against irradiation and transmutation, their compositional design flexibility allowing for reduction of high-activation elements, their high variety of other beneficial properties as well as the high variety of their manufacturing routes, possible applications of MGs in NF are manifold [16]. They range from radiation shielding of diagnostic equipment or thermoelectric devices [110] in or close to the reactor, support structures/bolts/standoffs for such devices, optical diagnostic mirrors with stable reflectivity [38,83,86, 111–114], springs and actuators [76,115], compliant mechanisms [58], diaphragms for pressure sensors [1], lubrication-free mechanisms [71, 72], gears with dimensions spanning several length scales [71,116], ball bearings [117], projectiles [118] and target capsules [119] for inertial fusion concepts or magnetic sensors/actuators [1,120]. The possible reduction of fuzz formation on plasma-facing components by MG coatings has been reported recently [26]. Applications necessitating neutron transparency, e.g. whenever neutrons need to reach breeding material, can be supported by MGs as well [121]. Forming in the UCL state can enable intricate shapes like parts necessary for RF antennae and waveguides or electromagnetic shielding [1,122]. Further applications include reusable metallic gaskets [76] or means of joining other materials [56,60,63,123–130] . The latter comprises, for instance, joining of MG or W parts to mitigate size limitations, joining of W to Cu-Cr-Zr heatsinks [62,124,125,130] or joining of thermoelectric devices to relevant sites in an NF reactor [110]. Reactor concepts using liquid-Li (breeding) blankets [131] or molten salts may benefit from the high corrosion resistance of MGs [30,132].

5.1. Categories of application

The utilisation of MGs for NF can essentially be divided into three categories. For the first one, already developed MGs can be directly applied in NF with little to no further compositional design exploiting the ability of MGs to outperform currently used crystalline materials in various places. A particular example are MG-based components in robotics [1,71,133,134], a fundamental part of maintenance of NF devices (cf. Figs. 2e,g,d). Other examples are diagnostic mirrors which retain their smooth surfaces and high reflectivity under sputtering conditions like those expected in NF [58,111–113,135–140] or neutron-transparent parts of pebble containers for tritium breeding.

For the second category, novel MG compositions are to be specifically designed to cater to the needs of the wide variety of applications under the special circumstances found in NF. As an example, MGs based on refractory metals like W or Ta can exhibit high densities necessary for effective radiation shielding combined with high-temperature stability (high T_g, T_X, ΔT_X) and the outstanding mechanical properties and modes of manufacturing of MGs discussed above [16,141,142]. Depending on their location in an NF device, MG mirrors could also fall under this category as do MG alloys designed towards resistance against corrosion by molten salts, liquid Li or its alloys.

In addition, as third category, MGs also have the potential to support NF while not being directly applied in an NF reactor. For example, MG membranes for separation of hydrogen isotopes [143,144] or MG electrodes for enhancing the hydrogen-evolution reaction [145] could facilitate the tritium self-sufficiency.

5.2. Glassy-crystalline synergies

In addition to monolithic MGs discussed so far, so-called MG composites have shown immense prospect [118,146–148]. They can alleviate some of the current shortcomings of MGs like limited plasticity or casting sizes. MG composites combine crystalline and glassy regions at different ratios and in different topologies (e.g. particles, fibres, grain boundaries). They can originate ex situ by adding pre-existing crystalline/glassy units to a glassy/crystalline matrix during the manufacturing process [148,149] or in situ when parts of the material crystallise during the manufacturing process or in operando [146,150]. Several studies (experimental and simulation) have shown the potential of both modes, e.g. for increased radiation tolerance [15,151,152] or enhanced plasticity [153]. An NF-relevant example for ex-situ composites are fibre- or particle-reinforced MGs for enhanced mechanical properties with W constituting the crystalline phase [154–157]. In-situ MG composites are an important alternative to NF-relevant monolithic refractory MGs when their high melting points hamper homogeneously glassy castings. Similarly, AM can yield MG composites instead of fully glassy parts [48,54,55].

For enhanced irradiation tolerance two modes of glassy-crystalline synergies may be distinguished. On the one hand, crystalline areas, e.g. precipitating following irradiation, within a glassy matrix can act as sinks for radiation-induced free volume [15]. On the other hand, glassy complexions between crystalline grains can act as sinks for irradiation-induced point defects [152,162,163]. Engineering both modes of defect sinks promises to be a worthwhile endeavour to increase the radiation-tolerance of metallic materials in NF.

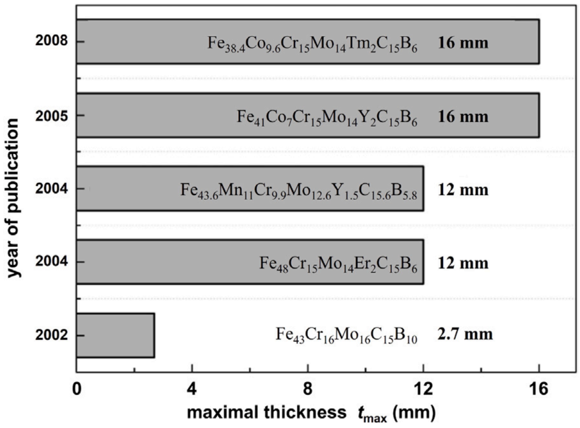

Fig. 3. Illustrative example of successfully increased of GFA (given in terms of the maximal casting thickness t_{max}) by compositional tuning of a family of Fe-based MGs with elevated-temperature resistance also called “amorphous steels” (adapted with permission from [158]). Optimisation for application in NF in this example would focus on the replacement of Mo, possibly by W, as has been done previously in case of crystalline steels [159].

Furthermore, MGs can also be utilised as precursors for relevant nano-crystalline or non-equilibrium crystalline phases with desired properties otherwise unobtainable [164–166].

5.3. Towards a development roadmap

Several of the unique properties of MGs which are promising to support various applications in NF are currently extrapolations based on a vast body of results outside of NF. For instance, the high corrosion resistance of many MGs demonstrated in different environments has not yet been tested against liquids proposed for application in NF, like liquid Li alloys or molten salts. Regarding irradiation, the promising experimental and simulation results published over the years are yet to be confirmed under conditions expected in NF devices. Furthermore, dedicated MG design to enhance these and other properties for environments prevailing in NF is yet to be pursued. To close these gaps and to leverage the full potential of MGs in NF, the development of a roadmap for their future systematic design and engineering is proposed.

Given the wide variety of alloy systems and manufacturing routes to be explored, applications to be covered and the demanding NF-specific materials requirements to be met, the workload needs to be distributed internationally among a multitude of research groups. In several respects, this endeavour can be considered analogous to joined international efforts in semiconductor development (e.g. International Technology Roadmap for Semiconductors, ITRS and International Roadmap for Devices and Systems, IRDS [167,168]) or the exploration of HEAs (e.g. Priority Programme SPP 2006: Compositionally Complex Alloys - High Entropy Alloys, Germany or DEEPSEA Development of HEAs-based Electrocatalysts for Clean Hydrogen Production via Seawater Splitting, EU [169]). NF-focussed HEA development is already pursued by many researchers [170–175] which can be adapted as blueprint for MG development for NF.

In the present case, a roadmap will include the identification of the potential benefits, limitations and needs for MG development in NF and can then be used to identify and down-select suitable MGs or MG families for further development for specific purposes in NF devices.

Purpose-driven development of novel MGs and optimisation of their GFA is often guided by a set of well-established empirical rules for enhanced GFA including Inoue’s rules [17] and the “confusion principle” [18,19] as mentioned above. Thermodynamic calculations (CALPHAD) are used to search for eutectic compositions at which GFA is

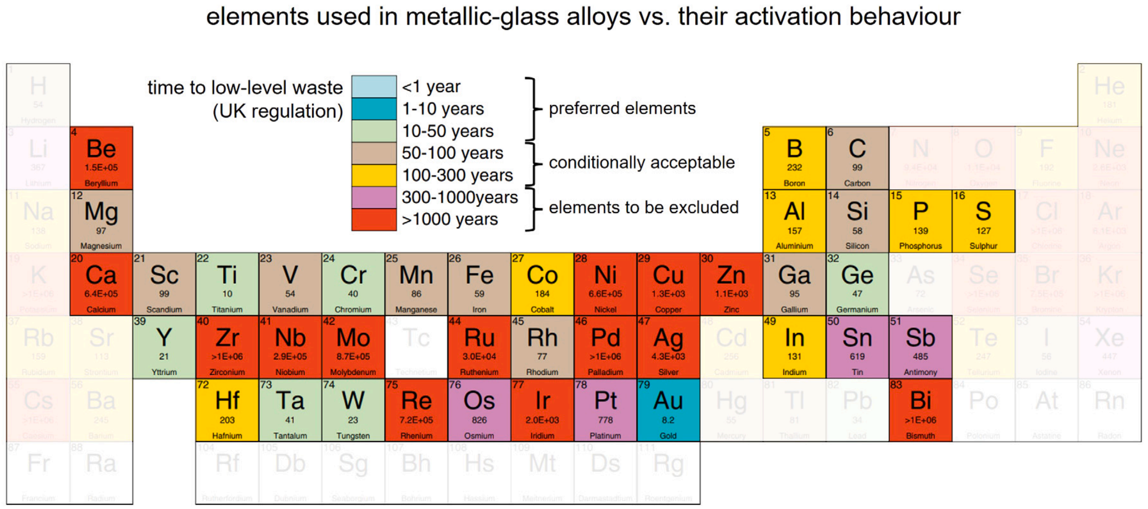

Fig. 4. Periodic table highlighting only those elements relevant for (bulk) glass formation [22]. The colour code indicates their activation behaviour (in terms of time to become low-level radiocative waste after irradiation during a full DEMO-type operation cycle (divertor cassette body) based on UK waste management criteria) [160]. For clarity, lanthanoid and actinoid elements have been omitted due to their comparably low relevance and mostly high activation behaviour [160]. MGs based on Ti, Ta or W seem to be a worthwhile target for further development with regards to NF. However, small additions of elements with less favourable activation behaviour, like B for high GFA and shielding efficiency, may be unavoidable and are “conditionally acceptable”. Elements shown in purple and red need to be avoided. It should be mentioned that other ways of presenting the activation behaviour of elements are possible, e.g. in terms of activity after a certain amount of time after service in an NF reactor. Activation depends on the location of the material in the reactor during service [161]. Periodic table adapted from [160] with permission.

usually found to be enhanced [1,17,28]. Modern methods like machine learning will accelerate the discovery of new compositions within the vast design space [142,176,177]. In addition, empirical experimental methods are used to fine-tune compositions towards higher GFA [23]. Fig. 3 illustrates the design process, exemplified by a family of Fe-based MGs.

For NF, additional constraints like transmutation/activation occur as major new driver. This excludes many elements that are known to enhance GFA in many relevant alloy systems, i.e. the design space is narrowed in the wrong regions (Fig. 4 shows a periodic table highlighting elements with relevance for high GFA [22] in combination with information on their activation behaviour [160]). In some cases this could just mean replacement of the affected element by one less prone to activation (e.g. W as replacement for Mo in the example shown in Fig. 3 as has been previously done in case of crystalline steels [159]). However, the replacement of one element in a multi-component alloy requires re-assessment of the relation between *all* occurring elemental pairs with this component in the alloy (mainly regarding heats of mixing and atomic sizes/inter-atomic distances [42,88,178]). If the base element of a family of alloys is concerned, the design process may need to recommence at a comparably low level or transition to a different alloy system to be considered. Newly designed compositions may also require updating related manufacturing processes.

Transmutation adds the unique circumstance of compositions changing in operando. Although, with respect to the “confusion principle”, this might even be considered beneficial [18,19,42] it needs to be thoroughly assessed how this will affect the design process.

The wide range of MG compositions in terms of chemistry, physical and mechanical properties as well as neutronics considerations cannot only provide alternatives where current NF materials are inadequate, but may adequately enable specific concepts in NF in the first place.

Reviewing the periodic table in Fig. 4, only a few “preferred” base elements like Ti, Cr, Ge, Y, Ta, W and Au seem available for MG alloy design. MGs based on Ti are well known and can be considered a valid starting point [179,180]. However, depending on the actual location in an NF reactor, the other alloy components are decisive. While close to the vacuum vessel known Ti-based bulk-MG compositions (e.g. $Ti_{40}Zr_{10}Cu_{36}Pd_{14}$ [179]) would be deployable, closer to the first wall some components need to be reduced (in this case mainly Cu [161]). Potential Cu-free replacements are under development [181]. Addition of low-activation V and Cr needs to be investigated. Following this design path, MG compositions derived from that of crystalline V-4Cr-4Ti (V44) alloys are another promising target for future developments [25].

For the harsh conditions in NF, special attention needs to be paid to the emerging classes of high-temperature and high-density MGs (HT-MGs/HDMGs) possessing high T_X, high shielding capability as well as high chemical and thermal stability [141,142,182]. Although refractory alloys (e.g. based on W or Ta) are particularly suited in this respect, their manufacture is usually challenging. AM may need to be favoured over traditional casting techniques but entails its own challenges and necessitates further research [52–54]. Emergent strategies like beam shaping and delay times (controlled laser-off periods) in powder-bed AM will help controlling the amorphous fraction, porosity and mechanical properties for targeted applications [50,54,55]. In addition to bulk materials, coatings need to be considered for refractory alloys as well as joining of smaller parts utilising the UCL state as discussed above.

In a sense, as combination of the two groups of materials, MG alloys based on so-called SMART alloys (Self-passivating Metal Alloys with Reduced Thermo-oxidation) are of interest for the event of a loss-of-coolant accident with simultaneous air ingress into the vacuum vessel which can cause the release of volatile and activated WO_3 into the atmosphere [183]. Crystalline SMART alloys are based on W and Cr and contain small amounts of Y and Ti/Zr (e.g. $W_{70}Cr_{28}Y_1Zr_1$ [184]) [25,183].

If an MG is found to be particularly beneficial for a specific application, potentially less-favourable activation behaviour can be offset by accepting a reduced service life of the component. While Fe-based MGs may fall under this category, Nb-Ni-based MGs would probably need to be disregarded due to the highly unfavourably activation behaviour of both elements [160,161]. Pd-based MGs, possessing very high GFA, may also need to be excluded due to cost and considerable content of high-activation Pd, Ni and Cu. Often used metalloids like P or Si can be acceptable, while B is necessary for shielding applications. However, as the amount of MGs used in NF is expected to be small compared to, e.g., EUROFER97 steel, their activation may be considered negligible altogether (EUROFER97, despite being designed for NF, may exceed low-level waste limits [160]).

Regarding simulations, irradiation-induced structural changes will need to be modelled for various projectiles (e.g. neutron, hydrogen and helium isotopes) at NF-relevant energies. The results will further inform alloy selection and design.

The roadmap will also need to include a techno-economical assessment of the production of MGs with identified relevance, especially where they can outperform crystalline materials in NF.

Going beyond MGs as amorphous materials in NF, amorphous ceramics or in-operando amorphisation of, e.g., W-borides can be aspects of a roadmap of even wider scope. These materials may be optimised using design insights adapted from MGs such that their properties do not deteriorate under, currently unwanted, irradiation-induced amorphisation or even improve.

6. Conclusions

Metallic glasses are a fascinating class of materials with high potential for a multitude of applications in nuclear fusion. Nevertheless, their optimisation towards the special requirements in this field needs to be expedited. To leverage the full potential of metallic glasses in nuclear fusion, the development of a roadmap for their dedicated design is suggested. Conventional design strategies for metallic glasses need to be adapted to implement the special requirements imposed by in-operando transmutation and activation. While certain alloy compositions and families require only minor modification, others necessitate a complete compositional redesign as well as adaptation of manufacturing processes. Addressing these challenges will be greatly enhanced by the application of advanced computational alloy design methodologies, incorporating thermodynamic modelling and machine learning. Regarding materials designed for the harsh conditions in NF, special attention needs to be paid to the emerging metallic-glass families like high-temperature and high-density metallic glasses. Depending on the particular application, development also needs to consider high shielding capability as well as high chemical and thermal stability. It is expected that the high corrosion resistance of metallic glasses will play a major role in the development of reactor designs employing liquid Li and its alloys as well as molten salts. An in-depth critical consideration of metallic glasses for nuclear fusion and their dedicated design and development with tailored chemistries and properties may lead to groundbreaking discoveries of new irradiation tolerant materials, extending the horizon of opportunities for materials for extreme conditions in general.

CRediT authorship contribution statement

Martin E. Stiehler: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Conceptualization. **Konstantinos Georgarakis:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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Data availability

No data was used for the research described in the article.

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