1.1 Introduction

Solids are one of the elementary states of matter, in which atoms are tightly bound to each other. The arrangement of the constituents (atoms/ molecules/ ions) of solid may be in an ordered manner or in an irregular fashion, resulting in different properties. Depending upon the atomic arrangement, solids can be classified as amorphous and crystalline. A solid is termed as “amorphous solid” when the atoms of a solid are arranged randomly with no long range order. On the contrary, a periodic arrangement of atoms results in a “crystalline solid” having long range order. The conditions under which a solid is formed and the type of material, are the major reasons behind the ordered or disordered structure of any solid. If the material is formed by slow cooling, the atoms get sufficient time to attain a stable configuration and thereby solidify in an orderly manner forming a crystal. On the other hand, rapid cooling results in a randomly arranged solid in which atoms get frozen-in and remain in a relatively high energy state as compared to crystalline solids. Depending upon the structure, the properties of crystalline and amorphous materials differ significantly. The properties of amorphous solids are isotropic in nature i.e., they remain same in all direction, whereas the properties of crystalline solids are direction dependent (anisotropic).

During crystallization, atoms gather in clusters in order to form a nuclei and the growth of these nuclei takes place subsequently. The stability of nuclei depends on thermodynamic properties (like temperature, pressure, etc) together with the chemical properties. Only stable nuclei, which have attained a critical cluster size, grow further in size. Both nucleation and crystal growth in combination with each other form crystallization process. The resulting structure may be a single crystal or poly-crystal with many grains. The atomic arrangement in a single crystal is periodic and replicates the same lattice structure throughout the crystal. A single crystal has translational, rotational, and reflection symmetry. Due to the lack of any defects, they possess interesting electrical and mechanical properties, though they are rarely found in nature. In contrast to this, poly-crystals contain many microscopic crystals (known as grains) of different sizes, separated by grain boundaries. Grain boundaries act as weak regions for breakdown of crystal. Conventionally, almost all metals and their alloys solidify into a crystalline structure, with many single crystal grains having different sizes. On the other hand, glasses, ceramics, polymers, thin films, etc., fall under the category of amorphous solids that lack any orderliness of crystals. Fig. 1.1 shows the arrangement of atoms/ molecules/ ions in crystalline, polycrystalline and amorphous solids.

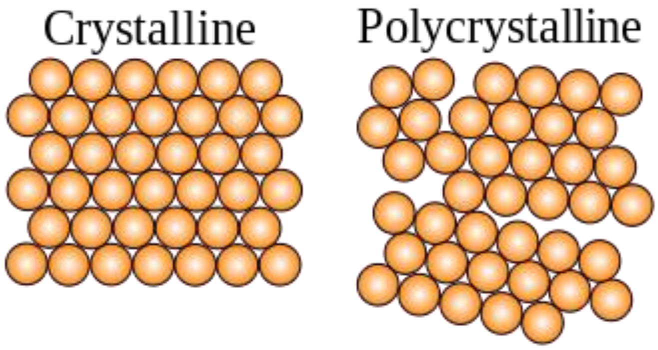
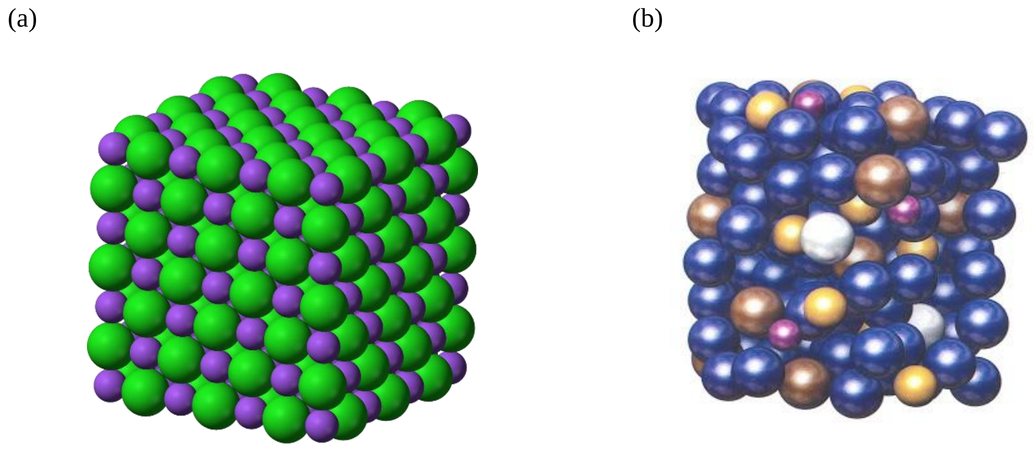


Fig. 1.1: Atomic/ molecular arrangement in Crystalline, Polycrystalline and Amorphous materials

(Source: https://en.wikipedia.org/wiki/Crystal dated 20/05/16)

1.2 Amorphous Alloys

A perfect disordered solid has a homogeneous structure throughout the solid i.e., the density of constituents is same in all directions, with no grain boundaries. Due to the absence of grain boundaries and other crystal defects amorphous solids possess excellent properties such as high mechanical strength, elasticity and poor chemical reactivity. The superior properties of amorphous materials can be enhanced by using metals as constituents. The ordered structure of metallic alloys can be transformed into disordered one, if the melt of alloy is cooled rapidly. Rapid cooling does not give sufficient time to the atoms/ molecules to arrange themselves in an ordered structure and the atoms gets solidified in an amorphous form. These materials that are structurally amorphous having metals as constituent are termed as "metallic glasses" or "amorphous alloys". Amorphous alloys, in contrast with metallic alloys, are homogeneous throughout the structure. This homogeneity enables them to achieve excellent properties that crystals lack. The structure of metallic alloy and metallic glass is shown in fig. 1.2. Amorphous alloys are formed when the cooling rate are high enough to supress the crystallization (~10^5 to 10^6 K/sec). They are structurally meta-stable materials i.e., they are in a relatively high energy state as compared to their corresponding crystalline phase. Rapid cooling increases the viscosity of a metallic melt, thereby decreasing their diffusivity and the melt gets solidified before acquiring a thermodynamically stable configuration. Like conventional glasses, metallic glasses also undergo glass transition. Glass transition is a transition in which the liquid dynamics slow down with lowering of temperature. Metallic glasses, in contrast with conventional glasses, are opaque, good electrical and thermal conductors.



Metallic Alloy **Metallic Glass**

Fig. 1.2: Structure of metallic alloy and metallic glass

(Credit: (a) http://www.stepbystep.com/difference-between-ionic-and-molecular-compound-88175/

(b) http://smartmaterials2009.blogspot.in/2009/09/glass.html

One of the most common method used for the synthesis of metallic glasses is melt-spinning. Melt spinning enables the formation of metallic glass ribbons at a very high cooling rate (~10^5

to 10^6 K/sec). Amorphous alloys with thickness greater than 1 mm are coined as "Bulk Metallic Glasses (BMGs)". BMGs require a relatively low cooling rate for their synthesis (≤1000 K/sec) as compared to metallic glass ribbons. The super-cooled liquid region, ($\Delta T_x = T_x - T_g$) for BMGs is larger than metallic glass ribbons, where T_x and T_g are crystallization temperature and glass transition temperature respectively. For example, Pd based amorphous alloy has ΔT_x value equal to 131K [1.1]. This makes BMGs more stable towards thermal fluctuations. The T_x, T_g, and enthalpy of crystallization (ΔH_x) are same for metallic glass ribbons as well as for BMGs having same composition. But the enthalpy of structural relaxation (i.e., glass transition) at T_g (ΔH_{relax}) is different for both ribbons and BMGs [1.2]. Since BMGs are made at lower cooling rates as compared to ribbons, they have more relaxed structures than metallic glass ribbons. Hence, the ΔH_{relax} values for BMGs are almost half than the ΔH_{relax} values for ribbon samples. BMGs are mostly synthesized by water quenching, copper mold casting, arc melting method, suction casting method, etc.

Ever since the discovery of the first Au-Si metallic glass by Duwez and coworkers in 1960 [1.3], many metallic glasses have been synthesized by rapidly quenching molten alloys. Initially, metallic glasses were limited to ribbons or wire like structures, due to the requirement of very high cooling rates. Later, in 1969, Pd-based amorphous alloy was synthesized at cooling rates less than 1000 K/sec [1.4]. First BMG was synthesized in 1974 by Chen et al [1.5]. They produced 1-3mm thick rods of Pd- and Pt-based alloys by quenching them at cooling rates of the order 10^3K/sec. Further in 1980, a Pd-based BMG was produced with 5mm thickness [1.6]. Following this, many Zr-, Fe-, Cu-, and Ti-based metallic glasses were formed at a further lower cooling rate (1-100 K/sec). Commercialization of metallic glasses begun in 1992, when a Zr-based metallic glass (also known as Vitreloy 1) was prepared at Caltech, for a research on metallic glasses, as aerospace materials [1.6].

1.2.1 Properties of Amorphous Alloys

The maximum achievable thickness of metallic glasses is limited, owing to the quick cooling rates required for their formation. Cooling metallic glasses at high cooling rates increase their viscosity significantly thereby paralysing their atomic mobility. This, in turn, reduces the contraction during cooling and makes the material resistant to plastic deformation. This structure make metallic glasses more flexible as compared to their crystalline counterparts. In comparison to conventional glasses, their brittleness is low.

The incorporation of different sized elements in metallic glass (more than three) helps in attaining larger sized amorphous alloys. More number of elements, of different sizes, increase randomness in metallic glass. Consequently, it becomes difficult for atoms to attain a stable configuration, and they get locked in an amorphous matrix (liquid-like) more easily upon cooling (even at lower cooling rates). Together with the number of components, the size difference between the components also play an important role in facilitating the formation of amorphous alloys. A significant difference in sizes of elements (≥ 12%) makes the atomic mobility difficult by increasing the inertia towards the attainment of stable configuration. The constituents must also have negative heat of mixing, in order to aid glass formation. These criteria for glass formation were given by Inoue et al [1.7].

i. Mechanical Properties

The amorphous structure allows metallic glasses to be independent of various defects present in crystals. Due to the homogeneous microstructure and absence of grain boundaries, metallic glasses have high strength [1.8-1.10], but less stiffness as compared to crystals. For example, the tensile strength of Vitreloy is almost twice than the strength of titanium [1.6]. Further Zr- [1.11], Cu- [1.12], Ti- [1.13], and Pd- based metallic glasses [1.14] have very high fracture toughness. High strength and flexibility makes them very resilient i.e., they can rebound high elastic strain energy. In spite of high strength, metallic glasses have high hardness, regardless of their amorphous structure, notwithstanding the inherent brittle character of glasses. However, one of the limitation includes the thermal sensitivity of the properties like ductility and toughness. Few Fe-based glasses loose ductility upon annealing without crystallization [1.15]. But this is not true for all metallic glasses. Due to these properties metallic glasses have high wear and abrasion resistance and they undergo low mechanical damping. As evident from fig 1.3 (a), the strength and elastic limits of glassy alloys are higher than that of titanium alloys and steel. Also it is visible form fig 1.3(b) that regarding the hardness, BMGs lie between metals and ceramics. Though they are less hard than conventional metals, they have good wear resistance as compared to metals.

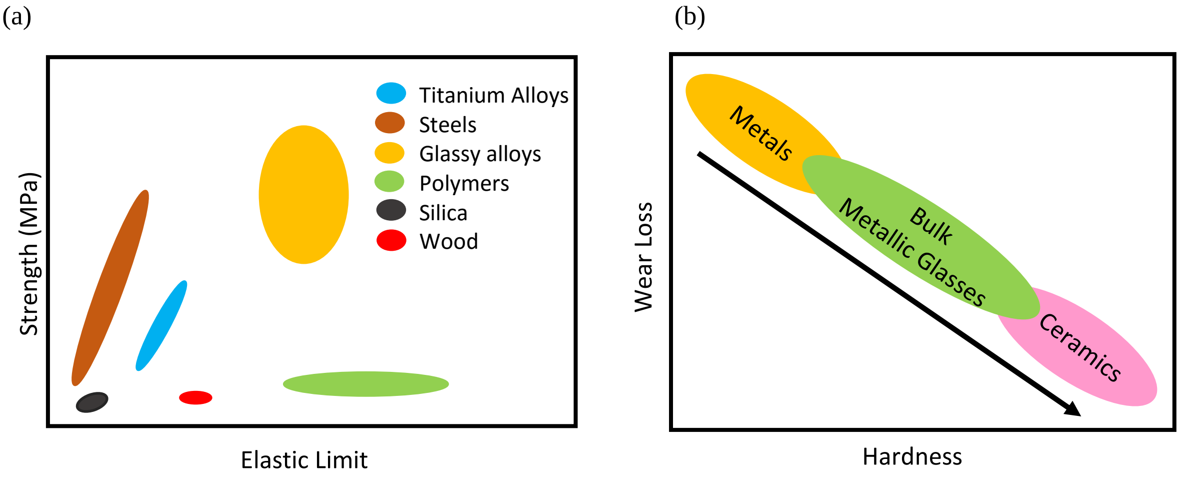


Fig. 1.3: Mechanical properties of metallic glasses

ii. Chemical Properties

The homogeneity in microstructure of metallic glasses avoid the segregation of like particles, and thus make the structure independent of grains and grain boundaries. Ultimately, this homogeneous microstructure and chemical arrangement contributes to a high corrosion resistant material [1.16]. In general, the corrosion resistance of metallic glasses is higher than a crystalline alloy. For example the corrosion resistance of Fe-based metallic glass is higher than Fe-Cr metallic alloy [1.17-1.19]. Further, addition of some corrosion resistant elements (like Mo, Nb, Ta, etc) to a metallic glass enhances its corrosion resistance.

iii. Magnetic Properties

Fe, Cu and Ni based metallic glasses possess soft-magnetic properties [1.19-1.23], i.e., they have narrow hysteresis loop (fig 1.4). They have low coercivity and a high susceptibility towards magnetization. They get magnetized and demagnetized very easily, and thus their hysteresis energy loss is very minimum. These materials have low eddy current losses when subjected to alternating magnetic field due to high electric resistivity. Due to their good ferromagnetic properties they can be used in transformer cores.

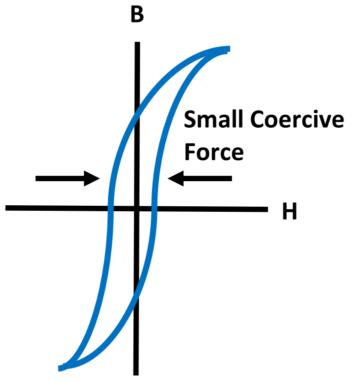


Fig. 1.4: Hysteresis loop of metallic glasses

iv. Electrical Properties

Metallic glasses have high electrical resistivity, which is insensitive towards temperature variations. Electrical conductivity of metallic glasses is lower than crystalline material and higher than conventional glassy materials. They have small (or negative) temperature coefficient of resistivity (TCR) [1.24-1.25]. This make them suitable for applications in electronic circuits.

v. Thermal Properties

Thermal conductivity of metallic glasses are lower than crystalline materials and higher than glassy materials. Thermal conductivity and thermal diffusivity of metallic glasses are almost independent of temperature, i.e., they show a weak dependence on temperature.

vi. Other Properties

Some of the Ti-, Co-, Zr- and Fe-based metallic glasses are biocompatible in nature owing to their good corrosion resistance in biological fluids [1.26-1.29]. Metallic glasses can be casted in various shapes and designs having good finishing. They have highly polished structure and durability. All these properties, in combination with each other, lead to many structural applications that are discussed in the next section.

1.2.2 Applications of Amorphous Alloys

BMGs can be casted in wide range of shapes and sizes such as rods, pipes, spheres, plates, etc. This moulding ability, along with fore mentioned properties, aids the applicability of BMGs in various spheres. Few applications are discussed below:

i. **Electronic Applications**: Their poor sensitivity towards electricity and temperature variations makes them a suitable candidate in electronic circuits as resistors, etc. They are used in cryothermometers, magnetoresistance sensor and computer memory due to their high electrical resistivity, and very small value of temperature coefficient of resistance. They also share their applicability as a superconducting material, due to their usefulness as high-field electromagnets.

ii. **Structural Applications**: The superior mechanical properties of BMGs such as high strength and resilient behaviour enabled their usage as automobile valve springs, sports goods such as tennis rackets, bicycle parts, skies and snowboards, etc [1.30]. BMGs are used as precision gears since they can easily be moulded into complicated shapes. Their excellent properties like wear resistance, low Young's modulus and high strength allows us to exploit them as aircraft parts, micro-geared motor, diaphragms for pressure sensor, etc. Fig. 1.5 shows some images for structural applications of metallic glasses.

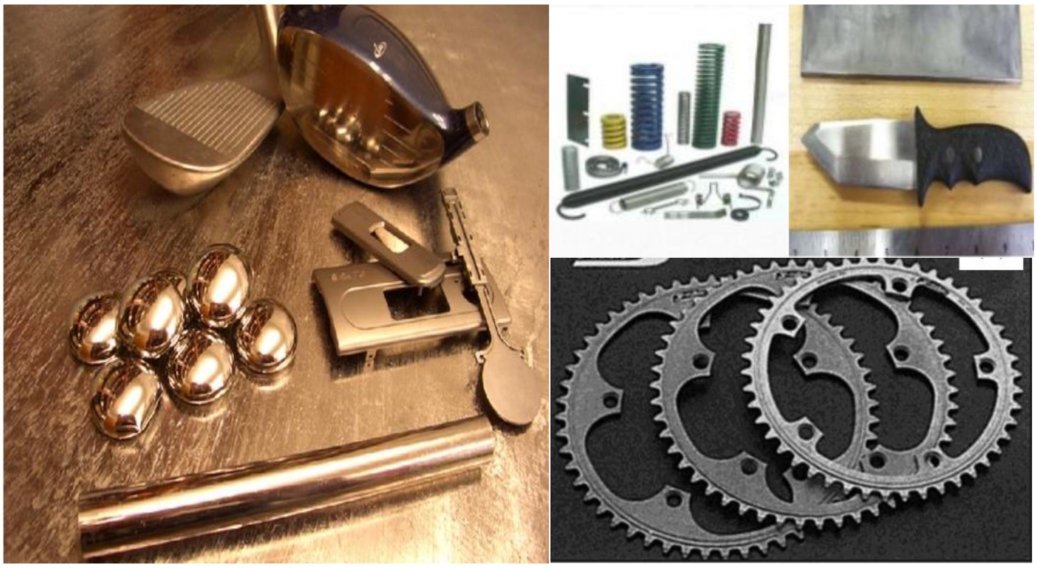


Fig. 1.5: Structural applications of metallic glasses

(credit: http://www.hindawi.com/journals/jma/2013/517904/fig2/,
http://www.slideshare.net/dipesh1996/metallic-glassesphysics,
http://www.slideshare.net/AnujDave3/application-of-metallic-glasses,
http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1516-14392015000601414)

iii. **Magnetic Applications**: Fe-based BMGs have found an application in power transformer cores in high power transformers, due to their soft magnetic character. Their magnetic character also enables them to be used as magnetic tape recording heads, sensitive and quick-response magnetic sensors or transducers [1.31-1.33].They are also used in making containers of nuclear waste disposals since their magnetic properties don't get affected by nuclear irradiations.

iv. **Biomedical Applications**: BMGs are used as bio-implants (dental and orthopaedic implants), as well as in medical devices such as surgical blades since they have low density, low Young's modulus, High strength and good casting properties. Along with these properties they also exhibit good corrosion resistance in bio-fluids and most of them are free from any cytotoxic elements.

Fig. 1.6: Biomedical applications of metallic glasses

(credit: https://www.drugwatch.com/2012/03/07/metal-on-metal-hips-linked-to-cancer/, http://www.slideshare.net/dipesh1996/metallic-glassesphysics, http://www.dailymail.co.uk/health/article-3104106/NHS-charges-patients-14-000-jump-queue-crucial-ops-Hospitals-letting-need-knee-hip-replacement-surgery-pay-skip-queue.html, http://orthoinfo.aaos.org/topic.cfm?topic=a00377)

v. **Chemical Applications**: The excellent corrosion resistance makes them suitable to be used in fuel cell separators.

vi. **Miscellaneous Applications**: Miscellaneous applications of BMGs include jewellery, mobile phone circuitry, watch cases and military applications such as aircraft and missile components, composite armor, electronic components, etc.

Fig. 1.7: Miscellaneous applications of metallic glasses

(credit: http://supercoolmetals.com/, http://www.slideshare.net/AnujDave3/application-of-metallic-glasses)

1.3 Experimental Techniques

The phase transitions occurring in metallic glasses, polymers, composites, etc can be studied by a thermo-analytical technique named as Differential Scanning Calorimetry (DSC). One of the important phase transition occurring in amorphous alloys, during heating, is crystallization. The analysis of crystallization event can be done by heating the glassy sample in a DSC at different heating rates. DSC provides the data of crystallized fraction with time or temperature. The experiments in DSC can be done either isothermally or non-isothermally [1.34-1.38]. The kinetic parameters of any thermally activated event can then be obtained by the analysis of the procured DSC data. Despite all the positive features of DSC, it has many limitations. One of the limitations of DSC is that the accuracy and precision, in the analysis of any complicated process, is lost. An improvised version of DSC that overcomes the limitations of conventional DSC is Modulated DSC (MDSC). Both DSC and MDSC operate on the same principle, except for the heating profile employed. MDSC heats the sample by at a non-linear heating rate that is a combination of a traditional linear heating rate superposed with a sinusoidal heating rate. Chapter 2 involves the detailed instrumentation of DSC, as well as MDSC, and the evaluation of different kinetic parameters using these instruments.

Chapter 2, further includes the detailed description of an instrument known as potentiostat, which is used to study the corrosion resistance of different glass forming alloys. Electrochemical polarization experiments are carried out using a Potentiostat. A typical potentiosat consists of three electrods viz, a reference electrode, a counter electrode and a working electrode. The material under consideration is set as working electrode. The potentiostat that is used to study the corrosion behavior of metallic glasses in present thesis is a Gammry reference 600 potentiostat, which uses calomel and graphite electrodes as reference and counter electrode respectively. The electrochemical reactions occurring in potentiodynamic tests involves movement of electrons from anode to cathode. This movement of electrons (current) is due to oxidation or reduction that predominates at the alloy surface. The corrosion current (i_{corr}), corrosion potential (E_{corr}) and corrosion rate are measured in order to study the corrosion resistance of any metallic glass.

1.4 Crystallization Kinetics of Metallic Glasses

Kinetics refer to the change in any thermally activated process such as crystallization, glass transition, etc, with respect to changing heating rate. A material, when subjected to any heating profile tends to change its phase in order to acquire a stable configuration. The atoms or molecules of the constituting elements tend to move towards a low energy state thereby transforming a random structure into an ordered one. This transformation of an amorphous material into a crystalline material, upon heating, is known crystallization. Crystallization is a first order phase transformation, i.e., it requires latent heat for the phase transformation. The kinetics of crystallization can be analysed by two methods, i.e., isoconversional and isokinetic methods. These methods give information about the kinetic process in terms of kinetic parameters, namely activation energy (E), pre-exponential factor (k_0) and Avrami exponent (n). Firstly, activation energy (E) is the energy required by the atoms/ molecules to overcome the barrier in order to form stable nuclei. A smaller value of E indicates that the material can be converted into a crystal by supplying a small amount of energy. In other words, an amorphous material can transform into a crystal easily if its activation energy is small. Secondly, Pre-exponential factor (k_0) indicate the number of jumps required to overcome the activation energy barrier. Again a smaller k_0 value represents higher tendency of molecules to overcome the barrier with a little effort. Thirdly, the Avrami growth exponent (n) gives information about the dimensionality of crystal growth, i.e., it tells whether the growth of nuclei is taking place in one, two, or three dimensions. Hence one can get the complete picture of crystallization process undergoing in an amorphous material upon heating, if E, k_0, and n are known.

Iso-conversional methods does not depend on any model for the calculation of kinetic parameters. Hence they are also known as *model free methods*. These methods provide E values depending on the degree of conversion (or the crystallized fraction (α)). Further *isokinetic methods* provide single E value for the entire crystallization process. Isokinetic methods are also known as *model fitting methods* since they depend upon some reaction models for the calculation of kinetic parameters.

Generally, metallic glasses are made up of two or more number of elements. Different elements crystallize at different temperatures. Hence a metallic glass can crystallize in a single step or it may undergo several crystallization events in order to crystallize completely. A multi-component metallic glass crystallizing in two or more steps must have different kinetics for all crystallization events. So, a single reaction model is not sufficient to explain entire crystallization process. Different models must be taken into account and their applicability must be checked beforehand. With regard to this, model free methods can be considered to be superior over model fitting methods.

The kinetics of crystallization of Ti-Cu-Zr metallic glass has been investigated in chapter 3 using MDSC technique. The two crystallization peaks obtained by performing MDSC runs at 1, 2, 4, and 8^0Cmin^{-1}, were studied using iso-conversional methods. Further, the variation of onset of crystallization temperature (T_x) and peak crystallization temperature (T_p) with heating rate. T_x and T_p varies in a power law behaviour with heating rate for Cu_{60} $Zr_{20}Ti_{20}$ metallic glass and shows a linear variation for $Cu_{60}Zr_{40}$ metallic glass. The power law variation is expressed as T_x (or T_p) = $T_0\,[\beta]^{y}$ [1.39]; where, β is the normalized heating rate, T_0 is the T_x (or T_p) at a heating rate of 1^0Cmin^{-1}. In addition to heating rate, the composition of a metallic glass also affects its crystallization temperature. It is observed that the characteristics temperatures shift towards higher values with increase in number of components.

1.5 Glass Forming Ability (GFA) of Metallic Glasses

Glass Forming Ability (GFA) is the ability of any metallic alloy to form glass. "Glass” is a general term given to the amorphous materials that undergo glass transition upon heating. Glass transition refers to the transition (or relaxation) of an amorphous material from a hard and brittle state into a rubbery like state. The material remains in a disordered state even after the transition and no latent heat is involved in this transition. Upon further heating the rubbery structure moves towards crystallization followed by melting. The temperature at which this glass transition occurs is known as glass transition temperature (T_g) and T_g is always lower than the crystallization temperature (T_x) and melting temperature (T_m). A metallic alloy can be transformed into a glass only if the formation of smallest detectable crystallized fraction (~ 10^{-6}) can be supressed. Glass formation can be achieved if a metallic glass is under-cooled below its T_g by rapidly solidifying it at a very high cooling rate. The cooling rate above which no crystallization occurs is known as critical cooling rate (R_c). R_c is the chief parameter which gives information about the GFA of BMGs. It depends on the composition of metallic glass.

Multi-component metallic glasses require low cooling rates for their synthesis as compared to binary metallic glass, because the degree of randomness is more in them. The limitation associated with the determination of GFA of BMGs by using R_c is that it is an experimental parameter. Several cooling experiments are needed to be carried out in order to correctly determine R_c. Another experiment parameter for determination of GFA is the critical dimension (or size) (Z_{max}). Z_{max} is the maximum attainable size of a completely amorphous material. The glass forming ability of metallic glasses basically depends upon three empirical rules [1.7]: a) three or more number of components, b) size mismatch (≥12%), and c) negative heat of mixing. These factors influence the GFA of metallic glasses significantly.

GFA of metallic glasses can be understood theoretically in terms of some parameters such as reduced glass transition temperature (T_{rg}), α, β, etc [1.40-1.41]. These parameters depend upon the characteristic temperatures T_g, T_x, T_m, etc. The applicability of the theoretically determined GFA parameters can be checked by correlating them with the experimental parameters R_c or Z_{max}.

Apart from these GFA parameters, few thermodynamic parameters are also there that explain the GFA of BMGs. One of the major thermodynamic parameter is Gibbs free energy difference (ΔG) between the super-cooled liquid state and the corresponding crystalline phase. ΔG is also known as the driving force of crystallization. A greater ΔG value indicates sufficient amount of driving force is available for crystal nucleation and hence crystallization is favoured. Whereas, the formation of nuclei becomes difficult when ΔG value is small due to unavailability of sufficient amount of energy required for nucleation. Hence, lower ΔG value favours the GFA of BMGs. The entropy difference (ΔS) also provide information about the GFA of metallic glasses. Higher value of ΔS indicates more disordered system and hence a better GFA and vice-versa.

Chapter 4 deals with the study of the thermodynamic behaviour of $Au_{49}Ag_{5.5}Pd_{2.3}Cu_{26.9}Si_{16.3}$ metallic glass on the basis of thermodynamic parameters ΔG, ΔH and ΔS. The thermodynamic parameter ΔG is calculated, as a function of temperature, using various expressions available [1.42-1.49] and the results are compared with the respective experimental values of ΔG in order to find the best theoretical expression of ΔG. The detailed formulation and the results for thermodynamic properties along with the comparison with the experimental results are given in chapter 4 of this thesis.

Further, chapter 4 reports some attempts made to study the GFA of Zr-based metallic glasses. Various GFA parameters together with the thermodynamic parameter ΔG (T_g) have been evaluated and their relationship with Z_{max} is studied for Zr-based metallic glasses. Also the GFA of Cu-Zr and Fe-based metallic glasses has been studied by minor substitution of alloying elements such as Al, Nb, Co, etc.

1.6 Bio-Corrosion Resistance of Metallic Glasses

Metallic glasses have excellent resistance towards degradation in aggressive and corrosive media. This ability allows them to be exploited as decorative items (where external appearances are important), containers to store acidic gases, etc. The applicability of metallic glasses can be extended to bio-medical implants if their bio-corrosive ability is known. One of the chief aspect of using metallic glasses as bio-implant is that it should not be carcinogenic or allergic to human body. Further its resistance against corrosion under the influence of bio-fluids such as saliva solution, blood plasma, etc., must be known beforehand. Simulated body-fluids are used for testing the bio-corrosion resistance of metallic glasses. The bio-compatibility of BMGs can be understood by performing potentiodynamic polarization experiments using potentiostat. The polarizations curves provides information about the corrosion current (i_{corr}) and corrosion potential (E_{corr}). Fig. 1.8 shows typical polarization scan. The electrochemical reactions occurring during anodic and cathodic polarization events involves the movement of electrons. Oxidation and reduction takes place in anodic and cathodic reactions respectively. The potential at which the oxidation and reduction rates become equal is known as E_{corr} and the corresponding current value that marks the initiation of anodic polarization is known as i_{corr}. Higher i_{corr} values indicate high rate of dissolution in the corrosive media, whereas higher E_{corr} values indicate high stability against corrosion.

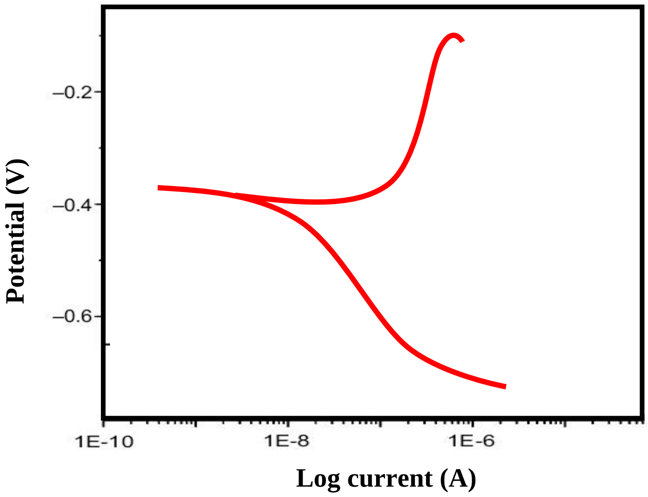


Fig. 1.8: Typical polarization curve

Chapter 5 deals with the bio-corrosion studies of $Co_{66}Si_{12}B_{16}Fe_4Mo_2$ and two Fe-based ($Fe_{32}Ni_{36}Cr_{14}P_{12}B_6$ and $Fe_{67}Co_{18}B_{14}Si_1$) metallic glasses. The polarization experiments were performed in four simulated body fluids in Gammry reference 600 potentiostat. Four simulated body fluids, namely artificial saliva solution (ASS), phosphate-buffered saline solution (PBS), artificial blood plasma solution (ABP), and Hank’s balanced saline solution (HBSS) were synthesized to perform potentiodynamic polarization studies of these metallic glasses.

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