

UNIVERSITY OF LJUBLJANA

FACULTY OF MATHEMATICS AND PHYSICS

Seminar

# **Metallic glass**

## **Abstract**

Researches are close to perfecting a new material called metallic glass that has puzzled scientists since the 1960s. The new material is said to be three times stronger than the best industrial steel and ten times springier. Metallic glass is created by cooling molten alloys extremely fast so that crystalization, which creates points of weakness, is stopped instantly, essentially giving the solid material the atomic properties of a liquid. Increased plasticity in amorphous- crystalline composites now promises new structural applications.

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# 1. Conventional metallic glass

Glass is a uniform amorphous solid material, usually produced when the viscous molten material cools very rapidly to below its glass transition temperature, without sufficient time for a regular crystal lattice to form. The term glass transition refers to the enormous slowing down in the dynamics of some liquids when their temperature is lowered.

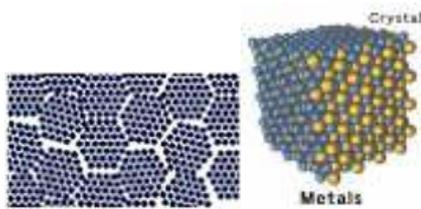
Amorphous materials are often prepared by rapidly cooling molten material. The cooling reduces the mobility of the material's molecules before they can pack into a more thermodynamically favorable crystalline state. Amorphous materials can also be produced by additives which interfere with the ability of the primary constituent to crystallize. For example addition of soda to silicon dioxide results in window glass.

In conventional metals, atoms crystallize into uniform three-dimensional patterns known as lattices. But about a half-century ago, materials scientists learned how to make glassy metals by cooling a metallic liquid so quickly that the internal atomic configurations froze before the atoms had a chance to arrange themselves into a lattice pattern. The processing method involved chilling molten metal at rates of  $1K/s$  to  $100K/s$ . Solidifies as a metallic glass with extraordinary properties. Its atoms seemed to be arranged in an irregular fashion without the long-range order characteristic of crystalline materials. The first metallic glass was a gold-silicon alloy ( $Al_{80}Si_{20}$ ), produced in 1957. It is less brittle than oxide glass and looks like a metal, so it is opaque, gray, shiny and smooth.

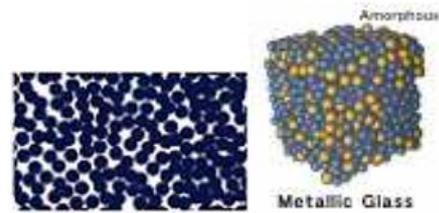
## 1.1. Extraordinary properties of metallic glass

The atomic structure is the most striking characteristic of the liquidmetal alloys as it fundamentally differentiates liquidmetal alloys from ordinary metals.

Liquidmetal alloys possess an amorphous atomic structure, which is truly unique (Figure 1 and Figure 2). By contrast to the crystalline structure, no discernable patterns exist in the atomic structure of the unique liquidmetal alloys (Figure 3). As such, properties superior to the limits of conventional metals can be achieved. In the tightly packed glassy structure, the displacement of atoms is obstructed. Their unusual atomic structure gives them distinctive mechanical and magnetic properties. Many traditional metals are relatively easy to deform or bend permanently out of shape because their atomic structure is periodic, where the layout of atomic elements shows repeating patterns over an extended range. This atomic structure is called crystalline and limits the overall performance of conventional metals. A metallic glass, in contrast, absorbs less energy upon stress and springs back to its original shape much more readily. With no crystal defects, metallic glass and its products have extraordinary properties like strength, hardness, toughness and elasticity (Figure 5) [2].

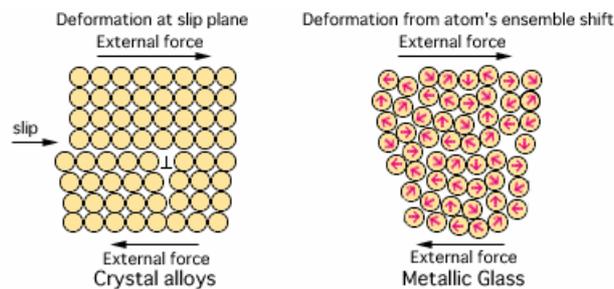


**Figure 1:** The atomic structure of conventional metal.



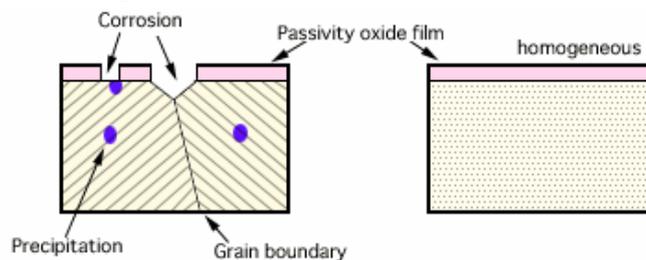
**Figure 2:** An amorphous atomic structure.

The different sizes of atoms lead to low free volume and therefore up to orders of magnitude higher viscosity than other metals and alloys in the molten state. The viscosity prevents the atoms moving enough to form an ordered lattice. The material structure also results in low shrinkage during cooling, and resistance to plastic deformation.



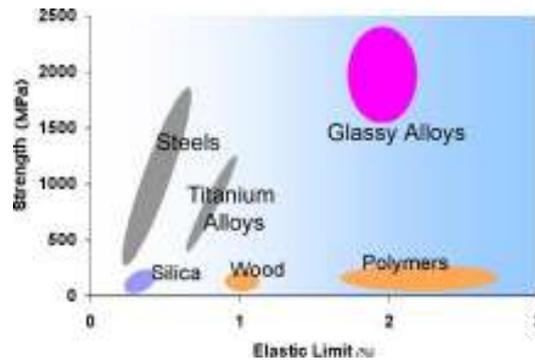
**Figure 3:** Metallic glass has an amorphous structure and moreover does not have a slip plane.

The absence of grain boundaries means that the material is resistant to corrosion and wear. It has good corrosion resistance because metallic glass has homogeneous microstructure and does not have grain boundaries (Figure 4). Moreover, metallic glass has superior abrasion resistance because metallic glass has a hard oxide surface by oxidation treatment.



**Figure 4:** Good corrosion resistance of metallic glass.

Metallic glasses possess soft-magnetic properties, specifically in the alloys of glass formers B, Si, P and ferrous magnetic transition metals Fe, Co, Ni. High electrical resistivity leads to low eddy current losses. Easy magnetization and demagnetization allow lower losses in applications, operation at high temperatures with minimal flux density reduction and annealing. In manufacturing, properties like these can have great appeal.



**Figure 5:** Typical strengths and elastic limit for various materials. Metallic glasses are unique [3].

## 1.2. Critical casting thickness

Heat conduction is slow in these materials. An important consequence of this was that metallic glasses could only be produced in a limited number of forms (typically ribbons, foils, or wires) in which one dimension was small so that heat could be extracted quickly enough to achieve the necessary cooling rate. As a result, metallic glass specimens (with a few exceptions) were limited to thicknesses of less than one-tenth of a millimeter.

In 1970s a new method of manufacturing thin ribbons of metallic glass was developed, by casting molten alloy of iron, nickel, phosphorus and boron onto a supercooled fast-spinning wheel. It has produced a continuous ribbon tens of microns thick. The material was commercialized in early 1980's and used for low-loss power distribution transformers.

Alternatively, droplets can be quickly frozen into a cold surface by splat cooling. This process was commercialized in the early 1980s for magnetic applications. The losses of power distribution in transformer cores are much lower. To enable bulk molding, the focus has been out on slow cooling rates to increase critical casting thickness.

## 2. Bulk metallic glass (BMG)

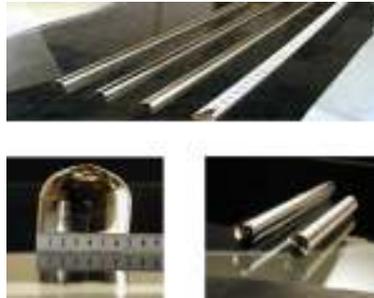
### 1.2. Development of bulk metallic glass

In 1969 amorphous spheres were formed of ternary palladium, copper, and silicon at critical cooling rates of  $100K/s$  to  $1000K/s$  with a diameter of  $0,5\text{ mm}$ . In some alloys the supercooled liquid range between the crystallization and glass transition temperatures was extended to  $40K$ . It enabled the first detailed studying of crystallization in metallic glasses.

In 1974 they obtained a critical thickness of  $1\text{ mm}$  in Pd-Ni (Co or Fe) and a slightly greater thickness with Au-Pb-Sb in 1982.

In the early 1980s they produced glassy ingots of palladium, nickel and copper with a diameter of  $5\text{ mm}$  using surface etching followed by heating and cooling cycles.

Since the 1980s the scientists have discovered strongly glass forming multi component lanthanum, magnesium, zirconium, palladium, iron, copper, and titanium alloys with large undercooling and low critical cooling rates of  $1K/s$  to  $100K/s$ . It is similar to oxide glasses. These properties allow an increase in time from *ms* to *min* before crystallization, enabling a greater critical casting thickness of  $1\text{ cm}$  by conventional molding.



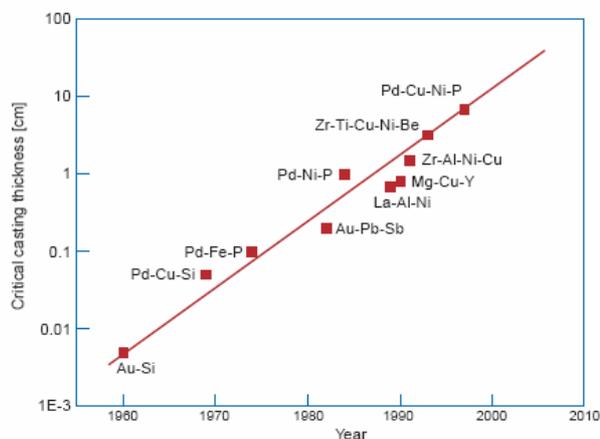
**Figure 6:** Bulk metallic glasses prepared from stabilized supercooled alloy liquids[4].

In 1988, alloys of lanthanum, aluminium, and copper or nickel were found to be highly glass-forming. Using Cu molds, they cast glassy up to  $5\text{ mm}$  thick, and in 1991 glassy up to  $9\text{ mm}$  thick. An extended supercooled liquid region (to  $127\text{ K}$ ) was achieved for Zr-Al-Ni-Cu with a critical casting thickness of  $15\text{ mm}$ .

In the 1990s, however, new alloys were developed that form glasses at cooling rates as low as  $1\text{ K/s}$ . These cooling rates can be achieved by simple casting into metallic molds. These bulk alloys can be cast into parts of up to several *cm* in thickness (the maximum thickness depending on the alloy) while retaining an amorphous structure [5]. They are suitable for casting or possibly molding into complex shapes for precision parts.

In 1992, the first commercial bulk metallic glass with critical casting thickness of up to  $10\text{ cm}$  known as Vitreloy 1 (41.2% Zr, 13.8% Ti, 12.5% Cu, 10% Ni, and 22.5% Be), was developed at NASA research of new aerospace materials.

The maximum sample thickness values are as large as about  $10\text{ cm}$  and the lowest critical cooling rate for the BMG formation is as low as  $0,1\text{ K/s}$  for the  $\text{Pd}_{40}\text{Cu}_{30}\text{Ni}_{10}\text{P}_{20}$  alloy.



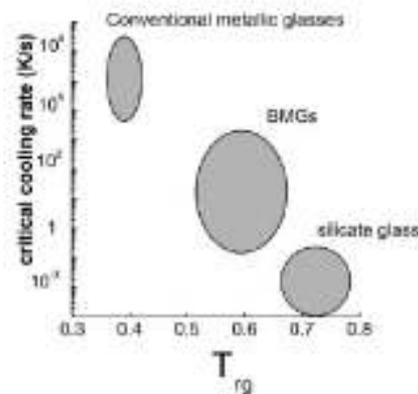
**Figure 7:** The critical casting thickness over the year in which alloys were discovered [2].

## 2.2. Thermodynamics, kinetics, and crystallization of BMGs

### Glass forming ability (GFA) of bulk metallic glasses

It was shown that a glass transition manifested in conventional glass forming melts could also be observed in rapidly quenched metallic glasses. The glass transition was found to occur at a rather well defined temperature which varied only slightly as the heating rate was changed. A material's glass transition temperature,  $T_g$ , is the temperature below which molecules have little relative mobility. It is the mid-point of a temperature range in which they gradually become more viscous and change from being liquid to solid.

It was predicted that a ratio, referred to as the reduced glass transition temperature  $T_{rg} = T_g/T_m$ , of the glass transition temperature  $T_g$  to the melting point, or liquidus temperature  $T_m$  of alloy.  $T_{rg}$  can be used as a criterion for the determining the GFA of an alloy. A liquid with  $T_g/T_m = 2/3$  becomes very sluggish in crystallization and can only crystallize within a very narrow temperature range. Such liquid can thus be easily undercooled at a low cooling rate into the glassy state. This criterion played a key role in the development of various metallic glasses including BMGs. Figure 8 shows a comparison of GFA of various glasses. One can see that some excellent bulk glass former has a GFA very close to silicate glasses.

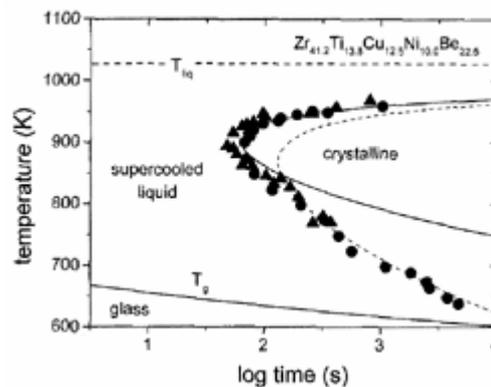


**Figure 8** : A comparison of GFA of various glasses [8].

### Thermal stability of bulk metallic glasses

Bulk metallic glasses have a very high resistance to crystallization. The novel BMG-forming liquids can now be studied in a much broader time and temperature range. It is now even possible to measure time-temperature-transformation (TTT) diagrams, such as the diagram

shown for  $Zr_{41.2}Ti_{13.8}Cu_{10.0}Ni_{12.5}Be_{22.5}$  (V1) alloy in Figure 10. In this diagram, the onset times for isothermal crystallization are plotted as a function of temperature. The diagram shows the typical C shape and a minimum crystallization time of 60 s at 895 K. For previously known glass-forming alloys, the times were of the order of milliseconds, resulting in the need for rapid quenching for vitrification. The TTT diagram of V1 reflects a very low critical cooling rate of about 1 K/s, which is lower than in earlier metallic glass-forming systems. The C shape is the result of the competition between the increasing driving force for crystallization and the slowing of kinetics (effective diffusivity) of the atoms. In simple liquids, atomic mobility is connected to viscosity. The driving force and the diffusivity and viscosity, respectively, are crucial parameters for understanding the glass-forming ability of supercooled BMG-forming liquids.



**Figure 9:** A time-temperature-transformation diagram for the primary crystallization of V1.

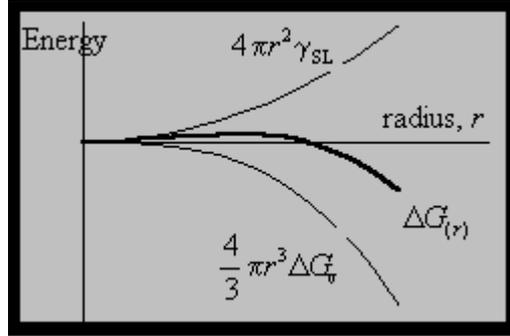
Researchers began to understand that the correct choice of elemental constituents would lead to amorphous alloys exhibiting critical cooling rates as slow as 1-100 K/s. These slower cooling rates mean that large pieces of metallic glasses can be fabricated. For the new types of metallic glass forming alloys the intrinsic factors of the alloy, such as the number, purities and the atomic size of the constituent elements, composition, cohesion among the metals, instead of external factors, such as cooling rate, play key roles in the glass formation. In general the glass forming ability tends to increase as more components are added to the alloy. The larger number of components in an alloy system destabilizes competing crystalline phase which may form during cooling. This effect frustrates the tendency of the alloy to crystallize by making the melt more stable relative to the crystalline phases. Summarizing the results of glass formation in multicomponent alloys, three empirical rules are proposed: multicomponent systems consisting of more than three elements; significant difference in atomic sizes with the size ratios above about 12% among the three main constituent elements; and negative heats of mixing among the three main constituent elements. They claimed that alloys satisfying the three empirical rules have special atomic configurations in the liquid state which are significantly different from those of the corresponding crystalline phase.

The ability to form a glass by cooling from an equilibrium liquid is equivalent to suppressing crystallization within the supercooled liquid. If steady state nucleation is assumed, the nucleation rate is determined by the product of a thermodynamic and a kinetic factor.

By assuming that solid phase nucleates as spherical ‘clusters’ of radius,  $r$ , it is shown that the net (excess) free energy change for a single nucleus,  $\Delta G_{(r)}$  is given by:

$$\Delta G_{(r)} = \frac{4}{3} \pi r^3 \Delta G_{l-s} + 4\pi r^2 \gamma_{SL} \quad (2.1)$$

where  $\gamma_{SL}$  is the solid/liquid interfacial energy.



**Figure 10:** The energy.

The critical radius  $r^*$  (defined as the radius at which  $\Delta G_{(r)}$  is maximum) is given by:

$$r^* = \frac{-2\gamma_{SL}}{\Delta G_{l-s}} \quad (2.2)$$

The associated energy barrier to homogeneous nucleation,  $\Delta G^*$  is found by substituting  $r^*$  into equation (2.1):

$$\Delta G^* = \frac{16\pi\gamma_{SL}^3}{3\Delta G_{l-s}^2} \quad (2.3)$$

We find de nucleatin rate:

$$I = ADe^{-\frac{\Delta G^*}{kT}} \quad (2.4)$$

where  $A$  is a constant,  $k$  the Boltzmann's constant,  $T$  the absolute temperature,  $D$  the effective diffusivity and  $\Delta G^*$  the activation energy which must be overcome for the formation of stable nuclei. The  $\Delta G_{l-s} = G_l - G_s$  is the free energy difference between the liquid state  $G_l$  and crystalline state  $G_s$ .  $\Delta G_{l-s}$  is therefore the driving force for diffusivity or viscosity (kinetic factor) and configuration (structural factor) are crucial parameters for understanding the glass formation in multicomponent alloy.

### Thermodynamic aspect

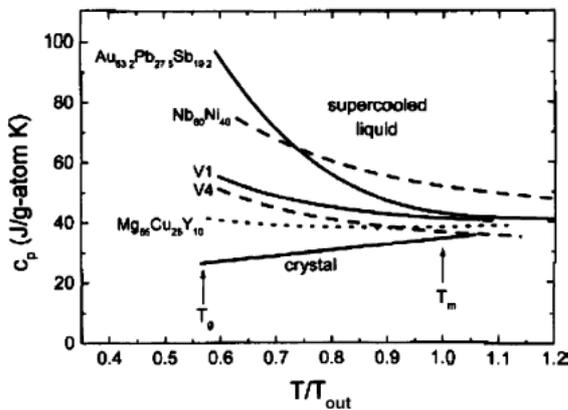
From thermodynamic considerations, bulk glass formers naturally exhibit a low driving force for crystallization in the supercooled liquid. The low driving force results in low nucleation

rates and therefore improved glass forming ability. Thermal analysis allows the determination of the Gibbs free energy difference  $\Delta G_{1-s}$  between the supercooled liquid and crystalline solid. Generally, it has been found that high glass forming ability is favored by small values of  $\Delta G_{1-s}$ , which can be calculated by integrating the specific heat capacity difference  $\Delta C_p^{1-s}(T)$  according to the equation [8]:

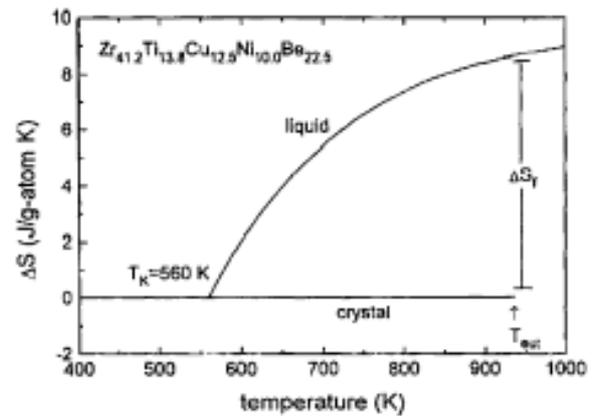
$$\Delta G_{1-s}(T) = \Delta H_f - \Delta S_f T_0 - \int_T^{T_0} \Delta C_p^{1-s}(T) dT + \int_T^{T_0} \frac{\Delta C_p^{1-s}(T)}{T} dT \quad (2.2)$$

Where  $\Delta H_f$  and  $\Delta S_f$  are the enthalpy and entropy of fusion, respectively, at the temperature  $T_0$ , the temperature at which the crystal and the liquid are at equilibrium. A low  $\Delta G_{1-s}$  means a small enthalpy of fusion and a large entropy of fusion. The large entropy is expected to be associated with multicomponent alloys because entropy is proportional to the number of microscopic states. The free energy at a constant temperature also decreases in the case of low chemical potential caused by the low enthalpy and high value of glass transition temperature  $T_{rg}$  as well as the large liquid/solid interfacial energy. Therefore, the increase in the number of alloy components leads to the increase in  $\Delta S_f$  and causes the increase in the degree of dense random packing in the liquid state. This is favorable for the decrease in  $\Delta H_f$  and the solid/liquid interfacial energy.

Researchers had systematically studied the thermodynamic functions of the typical bulk glass forming undercooled liquid, and the thermodynamic functions of the undercooled liquid were calculated using a  $1/T^2$  dependence of the specific heat capacity. Figure 11 shows the specific heat capacities in the supercooled liquid for several alloys. Figure 12 illustrates the calculated entropy of the undercooled V1 melt with respect to the crystal. The entropy of the undercooled liquid decreases with increasing undercooling until it reaches the entropy of the crystal at the Kauzmann temperature  $T_K$ . It is the temperature at which the difference in entropies between the liquid and solid phase becomes zero.



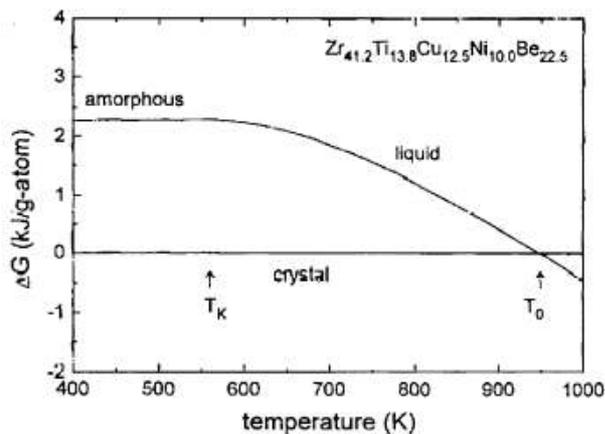
**Figure 11** : Specific heat capacities in the super cooled liquid for several alloys normalized to the eutectic temperature [8].



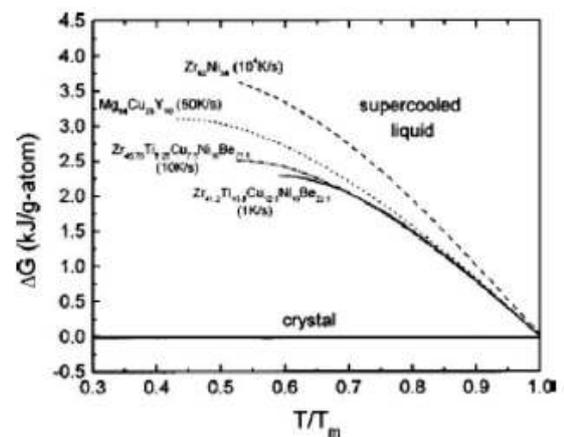
**Figure 12**: The calculated entropy of the  $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$  melt with respect to the crystal [8].

The calculated Gibbs free energy function with respect to the crystalline state is shown in Figure 13, from which it can be seen that for larger undercoolings, the real Gibbs energy difference becomes smaller due to the relative stabilization of the undercooling melt. This stabilization is attributed to the increasing specific heat capacity which arises from a decreasing free volume and probably a gradual gain of short range order in the alloy melt as well. The observed Gibbs energy difference is, for example,  $1,5 \text{ kJ/mol}$  at  $0,8T_m$ . This value is relatively small compared to conventional binary glass forming alloys like  $\text{Ni}_{50}\text{Ti}_{50}$  or  $\text{Nb}_{50}\text{Ni}_{50}$  at  $0,8T_m$ , where Gibbs free energy differences of  $2,5$  and  $3,2 \text{ kJ/mol}$ , respectively are found. The calculated Gibbs free energy difference between liquid and solid state stays small even for large undercooling. This relatively small Gibbs free energy difference is considered to be a contributing factor in the high glass forming ability of the alloy.

Figure 14 shows the Gibbs free energy difference between the supercooled liquid and the crystalline mixture for different glass forming alloys. The Gibbs free energy difference is compared with those of other typical eutectic, or close to eutectic, glass forming systems. The alloys show different critical cooling rates between  $1\text{K/s}$  for V1 and about  $10^4 \text{K/s}$  for the binary  $\text{Zr}_{62}\text{Ni}_{38}$ . The glass formers with the lower critical cooling rates have smaller Gibbs energy differences with respect to the crystal state than the glass formers with high critical cooling rates. The small free energy difference of these deep eutectic bulk metallic glass forming systems in the melt suggests that they already have a small free volume and a tendency to develop chemical short range order at or close to the melting point. These findings are consistent with the assumption that in multicomponent system the crystalline phases exhibit relatively large configurational entropies of mixing and with the fact that bulk metallic formers are very viscous and relatively dense liquids at the melting point and upon undercooling.

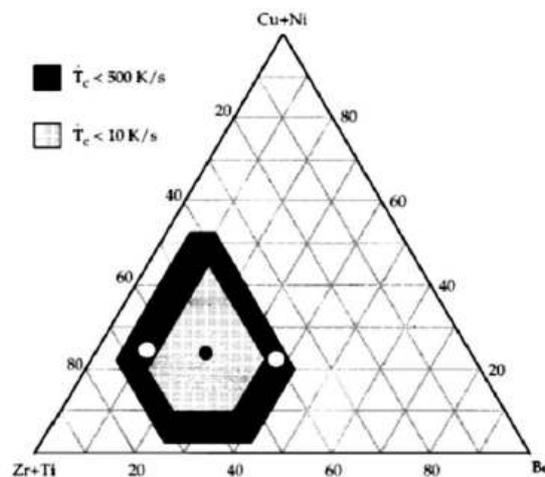


**Figure 13:** The calculated Gibbs free energy function with respect to the crystalline state [8].



**Figure 14 :** Gibbs free energy difference between the supercooled liquid and the crystalline mixture for different glass forming alloys [8].

The multicomponent alloy with excellent glass forming ability have low melting temperature. High glass forming ability alloys can be found among alloy compositions with deep eutectic, which form liquids that are stable to relatively low temperatures. Therefore,  $T_{rg}$  is a key parameter for glass formation and the homogeneous nucleation rate in the undercooled melt is a strong function of  $T_{rg}$ . Searching trough binary phase diagrams, one finds that the best candidates for good glass formers systems such as Pd-Si, Pd-P, Ni-Nb, Cu-Zr and Zr-Be, which all exhibit deep eutectics. In the ternary ZrTiCu, one finds the composition at the even deeper eutectic has better glass forming ability. The situation is further improved by taking quaternary alloys of Cu-Ti-Ni-Zr. Near the quaternary eutectic compositions, the good glass former of  $Ti_{34}Zr_{11}Ni_8Cu_{48}$  alloy with  $T_{rg} = 0,6$  and critical cooling rate of  $50-100 K/s$  was obtained. For higher order ZrTiCuNiBe alloy, a deeper eutectic features in the slightly off center portion of the quinary phase diagram shown in Figure 15, where the composition of initial  $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$  is marked. The thermodynamic competitiveness of the crystalline phases is diminished relative to the more accomodating liquid phase, resulting in a very deep higher order eutectic structure with high glass forming ability.



**Figure 15:** Quasi ternary cut through the Zr-Ti-Cu-Ni-Be phase diagram [8].

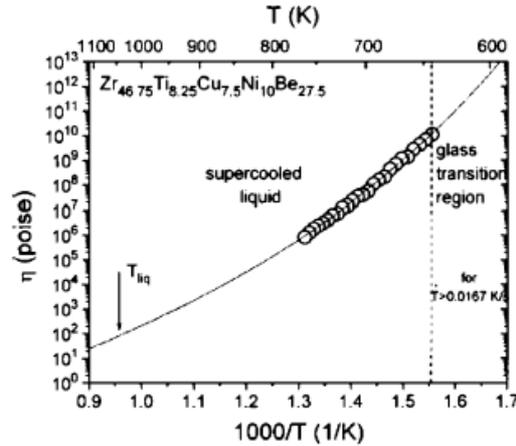
### Kinetics aspects

Glass transition from melt state to glass state cannot be described as a thermodynamic phase transition despite the discontinuity in the specific heat observed at glass transition. The glass transition temperature depends on the experimental cooling or heating rate during measurements. To better characterize the glass forming ability of BMG systems, one needs to study the crystallization kinetics in these alloys. From the perspective of kinetics, the temperature such as viscosity have a significant influence on the glass forming ability of an alloy system. A variety of techniques have been applied to measure viscosity from the equilibrium liquid down to the deeply undercooled liquid near  $T_g$ . Since the undercooled liquid alloys are relatively stable with respect to crystallization on laboratory time scales, viscosity can be measured in bulk glass forming systems in much wider temperature and time

scale than before. Figure 16 shows the viscosities of the BMG known as V4. All viscosity data can be described well with the relation [8]:

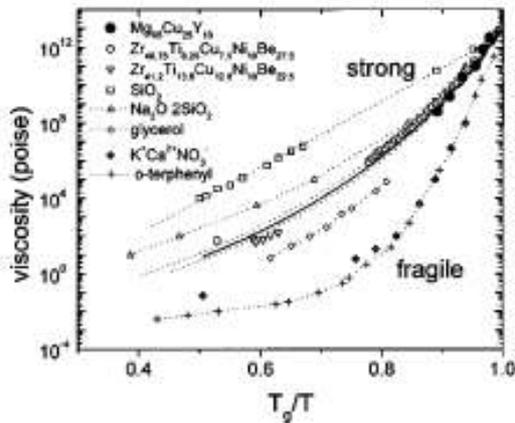
$$\eta = \eta_0 e^{\frac{DT_0}{T-T_0}} \quad (2.3)$$

Where  $T_0$  is the Vogel-Fulcher temperature, at which the barriers with respect to flow would go to infinity.  $D$  is known as the fragility parameter which identifies the property of a liquid.

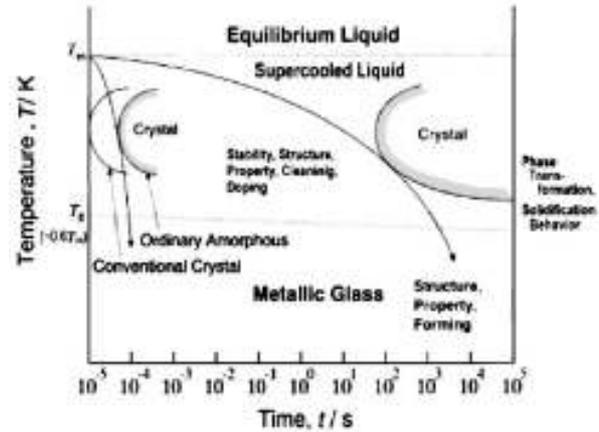


**Figure 16:** Viscosity as a function of temperature for the undercooled liquid of V4[8].

The change of viscosity of a liquid as a function of undercooling can be used to characterize and classify the different liquids, because it reflects the change of mobility of atom during supercooling. Figure 17 compares the viscosities of some typical BMG with a selection of typical non-metallic liquids.  $\text{SiO}_2$  is the strongest former with the fragility  $D$  of about 100. It exhibits a very small  $T_0$  temperature and a very high melt viscosity. On the other hand *O*-terphenyl is the typical fragile glass with a fragility of 5 and low melt viscosity. It shows a more abrupt change in the kinetic close to the glass transition. The available viscosity data of BMG forming liquids show that they behave closer to strong glasses than fragile glasses and have fragility ( $D$ ) approximately equal to 20. The melt viscosity of BMG is of the order of 2-5 *Pa s* and is about three orders of magnitude more viscous than pure metals, which usually have viscosities of the order of  $10^{-3}$  *Pa s*. The relaxation behavior of the BMG forming liquids is also similar to the nature of strong liquids. The strong liquid behavior implies high viscosity and sluggish kinetics in the supercooled liquid state. This greatly retards the formation of stable nuclei in the melt. Figure 18 illustrates the schematic diagram showing the high stability of the BMG forming supercooled liquid for up to several thousand of second. The conventional metallic glasses have nucleation kinetics in undercooled region such that the onset time for crystallization is in the regime of  $10^{-4} - 10^{-3}$  *s* at »noise« of the C curve. For BMG forming systems, there can be C curves with noises at time scale of the order of 100-1000 *s*.



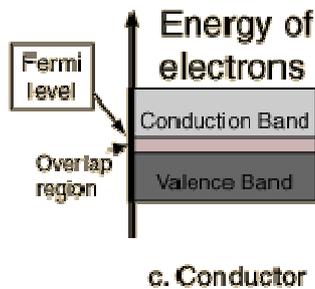
**Figure 17:** A comparison of viscosity of various glass forming liquids [8].



**Figure 18:** The schematic diagram showing the high stability of the BMG forming supercooled liquid for long periods reaching several thousand of seconds [8].

### Electrical conductivity of BMG

In terms of the band theory of solids, metals are unique as good conductors of electricity. This can be seen to be a result of their valence electrons being essentially free. In the band theory, this is depicted as an overlap of the valence band and the conduction band so that at least a fraction of the valence electrons can move through the material.



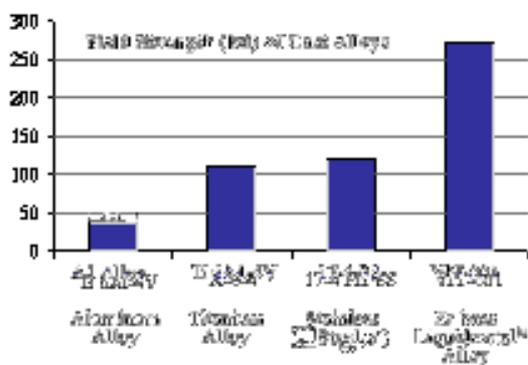
So the delocalised electrons are free to move throughout the structure. They can cross grain boundaries. Even though the pattern may be disrupted at the boundary, as long as atoms are touching each other, the metallic bond is still present. Liquid metals also conduct electricity, showing that although the metal atoms may be free to move, the delocalisation remains in force until the metal boils.

The electrical conductivity of bulk metallic glasses is smaller than in previously known glass-forming alloys. This suggests that an increasing number of electrons become localized in bulk metallic glasses as a result of directional bonds due to short range order. This effect, together with the small amount of free volume, makes the liquid more rigid with respect to shear flow and brings it energetically closer to the crystalline ground state.

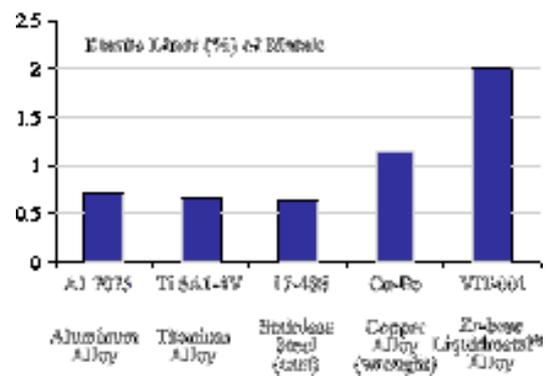
### 3. A variety of uses

As for now, the large number of different sized atoms and high viscosity leads to a free volume of only 1% at the melting point. In the solid, the difficulty with which atoms move over each other yields high corrosion and wear resistance.

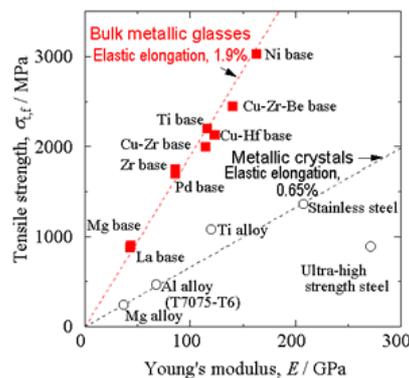
Zr based glasses have similar densities like crystalline steel and Ti alloys but high Young's modulus  $96 \text{ GPa}$  (Figure 21) and elastic strain to failure limit 2%. The glasses have high tensile yield strength  $1,9 \text{ GPa}$ . A high strength (Figure 19) to weight ratio makes them a possible replacement for V1, but with a much greater resistance to permanent, plastic deformation (fracture toughness). Less absorption and greater release of energy means that even after high load and stress deformation the material springs back elastically to its original shape.



**Figure 19:** Yield strength of Vitreloy compared to metal alloys [7].



**Figure 20:** Elastic limit of Vitreloy compared to metal alloys [7].



**Figure 21:** Relation between the Young's modulus and tensile strength of bulk metallic glasses (corresponding data of commercialized crystalline alloys are also shown as a comparison) [4].

Using products of amorphous metal alloys in variable bulk form is very extended. This shape memory ability enables the uses of the material in applications such as sporting equipment. The other principal areas for this products are luxury goods, electronics, medical and defence. The

BMGs, which exhibit high therm superb properties, have considerable potential as advanced engineering materials.



*Figure 22:* Zr-based BMGs in different shapes.

### **Golf club head**

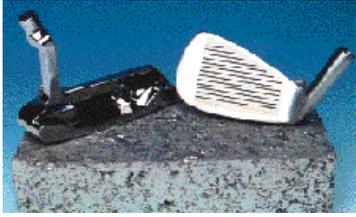
The first application was as golf club heads. Twice as hard and four times as elastic as Ti drivers. 99% of the impact energy from a BMG head is transferred to the ball compared to 70% for Ti. Higher strength to weight ratio allows mass to be distributed differently and enables various shapes and sizes of head.

### **Consumer electronics**

Vitreloy can also yield stronger, lighter and more easily molded casing for personal electronic products. In 2002 they began making components for liquid crystal display casings on cell phones. But costs became a problem. The company is now focusing on manufacturing select, higher-margin cell phone, mainly for Samsung and value added sports and medical products. Liquidmetal technologies casing have now been chosen for hand-held ultra personal computer screens. An agreement with Sony to develop a casing for digital still cameras has also been established. Liquidmetal technologies is also working with design firm to create a Vitreloy encased laptop that rolls up like a piece of paper.

### **Liquidmetal rebounds**

Liquidmetal Technologies is targeting leisure equipment that requires good rebound. They produce baseball and softball bats featuring its technology. The increased stiffness enhances energy return with 29% more power. Other potential applications in sporting goods include fishing equipment, hunting bows, guns, scuba gear, marine applications and bicycle frames. Vitreloy can also be used for watch cases to replace Ni and other metals, which can cause allergic reactions and jewelry.



**Figure 23:** Liquidmetal golf-club heads are fabricated from an amorphous metal alloy (at the bottom) that has excellent rebound and vibration-absorbing properties.



**Figure 24:** A tennis racket that uses Vitreloy in the hands of Andre Agassi [2].

### **Medical applications**

Vitreloy has a highly biocompatible, nonallergenic form, which is ideal for corrosion and wear resistant medical applications. They are producing ophthalmic scalpel blades using Vitreloy. They are higher quality but less expensive than diamond, sharper and longer lasting than steel. They are more consistently manufacturable, since they are produced from a single mold ready for use. Other edged tool applications include knives and razor blades.

### **Defence**

This technologies is used to develop military materials that are stronger, lighter and more effective at high temperature and stress. BMG composite KEPs can replace depleted uranium penetrators in antitank armor piercing projectiles because of their similar density and self sharpening behavior. Unlike most crystalline metal projectiles, which flatten on impact. The sides of BMG composite KEPs shear away underdynamic loading.

## 4. Conclusion

There are good prospectives for BMG materials whose properties favor easier, cheaper processing for more common place applications. For example, they found the first bulk glassy alloy with tensile strength over  $2\text{ GPa}$  which is higher than that for Mg, Pd and Zr based alloys, with distinct plastic elongation in a less expensive Cu based alloy system. This high strength alloy can be formed by Cu mold casting.

The promising work, together with developments greatly improves the prospects for the discovery of new BMGs with properties that will enable practical manufacturing. In turn, this is likely to open a new sphere of potential applications. In a word, metallic glass opens a new field in materials science.

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