International Journal of Science, Environment and Technology, Vol. 5, No 4, 2016, 2209 – 2216
ISSN 2278-3687 (O)
2277-663X (P)

POTENTIAL APPLICATIONS OF METALLIC GLASSES

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Abstract: Metallic Glasses are considered to be the materials of the future. These new materials are said to be stronger and much springier than the best industrial steel. This article presents a short review of metallic glasses: the general knowledge, the history and methods of preparation of metallic glasses, the remarkable properties along with potential applications and problems exist in studying of these new materials.
Keywords: Glasses, metallic, non-crystalline solid, elastic, strength.

1. INTRODUCTION

Mention "glass", and a window pane comes to mind. To scientists, a glass is any material that can be cooled from a liquid to a solid without crystallizing. Most metals crystallize as they cool, arranging their atoms into a highly regular spatial pattern called a lattice. But if crystallization does not occur, and the atoms settle into a nearly random arrangement, the final form is a metallic glass. Unlike common glasses, such as window glass, which are typically electrical insulators, metallic glasses have good electrical conductivity. With no crystal defects, metallic glasses have a lot of remarkable properties, which promise a lot of applications in engineering. However, study of the structure and study how to create a metallic glass with a large size is a challenge for scientists. Thus, although the first successful fabrication of metallic glasses was done more than 50 years ago, these materials still have a very large attractiveness in science and engineering. The objective of this article is to introduce the general knowledge, the problems have not been resolved and the potential applications of these new materials.

2. HISTORY OF METALLIC GLASSES

How to create a metallic glass? The answer is to give the metal atoms not the slightest chance to form a crystal. This means to cool the material superfast.The formation of the first metallic glass of $Au_{80}Si_{20}$ was reported by Duwez and co-workers at the California Institute of Technology in 1960 [1]. Rapidly quenching a $Au_{80}Si_{20}$ alloy, using "splat-cooling" to

*Received July 2, 2016 * Published Aug 2, 2016 * www.ijset.net*

produce a cooling rate on the order of 10^6 K/s, suppressed crystallization and produced thin wafers of metallic glass. Over the next two decades glass forming systems based on Fe, Pd and Ni were discovered. Cooling rates of 10^4 to 10^6 K/s were required for all of the glass forming alloys. One way to do rapid cooling is by single-roller melt spinning. In this process, the alloy is melted (typically in a quartz tube) by induction heating, and then forced out through a narrow nozzle onto the edge of a rapidly rotating chill wheel (typically made of copper). The melt spreads to form a ribbon, which cools rapidly because it is in contact with the copper wheel. The high cooling rates required sample to be thin, typically about 50 μm. The thin samples limited the types of mechanical test that could be performed on these early glasses.

In 1969 Chen and Turnbull made a $Pd_{78}Cu_6Si_{16}$ metallic glass with a critical cooling rate of 10^3 K/s [2]. This glass could be cast into 0,5 mm rods, which allowed more extensive mechanical testing to be performed. It has been shown that metallic glasses have a series of remarkable properties, but too small thickness limited their applications. To enable bulk molding, i.e. metallic material that can be made glassy with a thickness of 1 mm or more in all dimensions, the focus has been on slowing cooling rates to increase the critical casting thickness.

Inoue (Institute for Materials Research, Tohoku University, Japan) indicated the key empirical criteria for slow crystallization kinetics [3], include:

• The alloy has to be made of three or more components, leading to complex crystal units with higher potential energy and lower chance of formation.

• The atomic radius of the components has to be significantly different (over 12%), to achieve high packing density and low free volume.

• The combination of components should have negative heat of mixing, inhibiting crystal nucleation and prolonging the time the molten metal stays in supercooled state.

• The alloy should be eutectic.

Slower crystallization allows decreased critical cooling rate and enables stable bulk metallic glass formation and fabrication by conventional casting techniques. In the late 1980s, the Inoue group developed new groups of multicomponent metallic glass systems with lower cooling rates in Mg-, Ln-, Zr-, Fe-, Pd-, Cu-, Ti- and Ni- based systems. They found exceptional glass forming ability in La-Al-Ni and La-Al-Cu ternary alloys system [4]. By casting the alloy melt in water-cooling Cu molds, the cylindrical samples with diameters up to 5 mm were made fully glassy in the $La_{55}Al_{25}Ni_{20}$ alloy. Similarly, the $La_{55}Al_{25}Ni_{10}Cu_{10}$

alloy, fabricated by the same method, was even big with a diameter up to 9 mm. In 1993 Peker and Johnson, at the California Institute of Technology, discovered a metallic glass with a critical cooling rate of 1 K/s. This glass, which has a nominal composition of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ and goes by the trade name Vitreloy 1, could be cast in evacuated quartz tubes with a diameter of up to 16 mm [5]. This work together with the work of the Inoue group can be considered as the starting point for the use of bulk glassy materials in structural applications. By this time the scientists have obtained metallic glasses with a thickness of 50-80 mm (Pd-Cu-Ni-P, Pd-Pt-Cu-P [6]). However, the main metals (Pt, Pd) in these alloys are precious, so their price is quite expensive, not widely for use. Finding compounds based on cheaper metals as well as methods of preparation of metallic glasses with larger sizes is still a conundrum waiting for answer from scientists.

3. PROPERTIES AND POTENTIAL APPLICATIONS OF METALLIC GLASSES

Structural features of glassy materials have determined many characteristics such as good mechanical properties, useful magnetic properties and unique chemical properties, which have not been achieved from crystalline materials.

The superior mechanical properties of metallic glasses are the most promising for applications. In particular, they tend to be stronger than crystalline alloys of similar chemical composition, and they can sustain larger elastic deformations than crystalline alloys. Metallic glasses derive their strength directly from their non-crystalline structure, which does not have any of the defects (such as dislocations) that limit the strength of crystalline alloys. Tensile tests on metallic glasses revealed strength approaching theoretical values, with $\sigma \sim E/50$ (σ- the tensile yield strength and E- Young's modulus) [7]. In tensile loading, the elastic strain limit ε_{el} of metallic glasses is about 2%, much higher than that of common crystalline metallic alloys, where $\varepsilon_{el} \leq 1\%$ (Fig. 1). The high elastic strain limit of metallic glasses combined with a high yield strength, and fracture toughness make metallic glasses ideal for applications where the storage of high densities of elastic energy is needed. Furthermore, metallic glasses are true glasses, which mean that they soften and flow upon heating. This allows for easy processing, such as by injection molding, in much the same way as polymers. As a result, metallic glass alloys have been commercialized for use in sports equipment, medical devices, and as cases for electronic equipment.

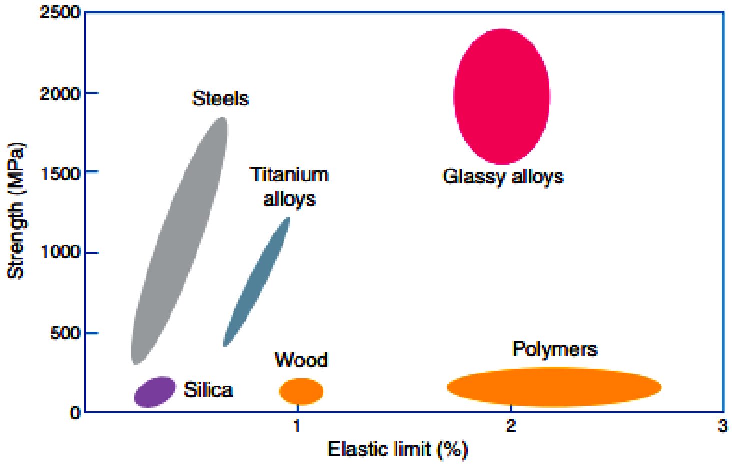

Figure 1. Metallic glass alloys combine higher strength than crystalline metal alloys with the elasticity of polymers [8]

The first application was as golf club heads. In addition to the merits like low density and high strength-to-weight ratio, other properties such as low elastic modulus and lower vibrational response provide a softer, more solid feel for better control when a golfer strikes the ball. The negligible hysteresis loss of metallic glass means that less energy is absorbed by the club head at impact, so more energy is transferred to the ball. According to the literature of the metallic glass golf plate manufacturer, steel club heads transfer about 60% of the input energy to the ball and titanium transfers 70%, whereas the metallic glass transfers 99% [9]. Other potential applications in sporting goods include fishing equipment, hunting bows, guns, scuba gear, marine applications and bicycle frames.

In addition to sporting goods, the new family of materials could also be promising for other more serious applications. Under a contract from the US Army Research Office, for example, researchers in USA are working to develop manufacturing technology for metallic glass tank-armor penetrator rounds to replace the current depleted uranium penetrators, which are suspected of biological toxicity. The tungsten composite penetrator exhibits self-sharpening behavior similar to that of oxide glasses and is highly efficient in piercing armor plates.

The possibility of molding into components with thin sections allows metallic glasses to challenge magnesium alloys in the electronic appliances market. With the trend of miniaturization of personal electronic devices such as MP3 players and personal digital assistants, there is a pressing need to make the casing thinner while retaining sufficient mechanical strength. Metallic glasses exhibit obvious advantages over polymeric materials and conventional light alloys. Mobile phones and digital still cameras with metallic glass casing are already developed.

The absence of grain boundaries means that metallic glasses are resistant to corrosion and wear. They have good corrosion resistance because these materials have homogeneous microstructure and do not have grain boundaries. Moreover, metallic glasses have superior abrasion resistance because they have a hard oxide surface by oxidation treatment. On the other hand, metallic glasses have a highly biocompatible, nonallergenic form, which is ideal for corrosion and wear resistant medical applications. Scalpel blades produced from metallic glasses 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.

A very promising use is medical implants [10]. Because the metallic glasses are so lightweight and tougher than high-quality steels or titanium alloys, they make very good implants, for example as prosthetic hip joints. Another application is degradable implants. Mg-Zn-Ca metallic glasses are not only biocompatible, but also biodegradable. Mg, Zn, and Ca all occur naturally in the body and they can be absorbed by the body without harm. In the case of Mg-Zn-Ca glasses, they are absorbed at a rate of about a microgram a day. This allows their use as nails to hold fractured bones together and that slowly dissolve as the bone grows.

Metallic glasses possess soft-magnetic properties, specifically in the alloys of glass formers B, Si, P and ferrous magnetic transition metals Fe, Co, Ni [11]. In a crystal, imperfections can make it difficult for a soft magnetic material to change its magnetization in response to an external field. This requires additional energy, and results in energy losses during the switching process. Not so in magnetic glasses, which are far more homogeneous and therefore show lower losses. Consequently, magnetic metallic glasses are used in transformer cores, where they are very economical in converting high voltages down to household levels. They are also great sensors for magnetic fields, for example as tiny compasses.

4. PROBLEMS EXIST IN STUDYING OF METALLIC GLASSES

There are many unresolved problems regarding studying of metallic glasses, which deserve further study. One can list the following problems:

The noncrystallinity of glasses defines their excess Gibbs free energy with respect to the crystalline state and constitutes the origin for the so-called structural relaxation -

spontaneous local atomic rearrangements occurring in all types of glasses and leading to significant changes in their properties. For example, the shear viscosity can increase by five orders of magnitude as a result of structural relaxation [12]. This decrease in the atomic mobility almost completely suppresses the deformability, which leads to embrittlement, thus deteriorating the technological properties of metallic glasses. Despite decades-long investigations of the structural relaxation in metallic glasses, its microscopic mechanism still remains controversial.

Metallic glasses have already found use in applications such as micromotors and sporting equipment, but have not yet been utilized as building materials. One primary reason for this is the tendency of metallic glasses to fail catastrophically under applied stress with almost small plastic deformation [13]. In order for metallic glass to become a widespread structural material, mechanisms for improving plasticity must be developed. In general, bulk metallic glasses can show super-plastic deformation at high temperature conditions, while at room temperature they are not ductile and tend to fail suddenly when loaded in tension. The disadvantage of low plasticity has been alleviated by the production of two-phase microstructures consisting of a ductile reinforcement material in a glassy matrix. Bulk metallic glasses can be formed and processed similar to polymers by thermoplastic processing techniques. For future applications, the interplay between structural developments and mechanical properties needs to be investigated in more detail in order to develop new structural glassy materials.

It is reported that the atomic structure and thus the mechanical properties of bulk metallic glasses can be transformed by the influence of deformation [14]. To apply bulk metallic glasses to engineering, it is important not only to determine their strength properties and workability but also to propose a way to maintain or improve the mechanical properties after deformation in order to expedite the industrial use of bulk metallic glasses. In particular, it is necessary to sustain their original fracture strength even after a thermal process such as annealing or hot working.

Metallic glass alloys have a variety of potentially useful properties. However, as present, they have high cost relative to many common alloys, so focus is shifted to develop bulk metallic glasses using cheaper raw materials.

5. CONCLUSIONS

Metallic glasses have not always been easy systems to study. It took more than 30 years after the original demonstration to come up with ways to fabricate them in bulk form. Once that problem was solved, metallic glasses have slowly but surely made them into applications. Despite numerous investigations of the structural and properties of metallic glasses, they still remain unintelligible. However, as the yield strength of bulk metallic glasses is up to one order of magnitude higher than in polymers and the elastic strain limit is double that found in conventional metallic alloys, it is likely that bulk metallic glasses or composites will replace some conventional materials in our everyday life in the near future.

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