Unique properties of a new Al/Sn Metallic Glasses obtained by drop cooling

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Abstract. Poorly documented Al/Sn - noncrystalline - atomic conglomeration such as observed in bimetallic glasses (bMGs) is studied. The conglomerate is obtained by inducing a Al/Sn non crystalline structure, which can be produced by a rapid cooling process called quenching. We designed and built a device that ensures the desired large-scale cooling rate, thereby creating the Al/Sn atomic conglomeration necessary for the test. The testing bMGs is made to determine Al/Sn metallic glass specific properties in dependence on the purity of the material, cooling rate and other processing factors. It is believed that the combination of aluminium and tin can result in new metallic glass compositions where Al/Sn combination of strength, hardness, corrosion resistance and other properties offer advantages over its crystalline counterparts. This study is part of an effort to explore new bMGs compositions, processing techniques and glassforming ability of Al/Sn metallic alloy materials for future applications in aerospace electronics and medical devices.

Keywords: bimetallic glass, Al/Sn, non-crystal structure, glass-forming ability

I. INTRODUCTION

Bimetallic glasses, often referred to as metallic glass (improperly amorphous metal), is a unique type of material that combines properties of both metals and glass. Unlike conventional crystalline metals, which have a highly ordered atomic structure, metallic glasses have a disordered, non-crystalline atomic arrangement similar to that of glass. The mentioned alloy is a unique type of material that combines properties of both metals and glass, [8]. Tin (Sn) is a common solder due to its low melting point, good wetting properties, and compatibility with aluminium (Al) and metals commonly used in electronics. Proper bonding between Sn and Al is crucial for reliable connections and the overall performance of electronic devices. Aluminium (Al) –Tin (Sn) alloys are potential lead free bearing materials, widely used in automobile and marine applications due to their embedability properties i.e. the ability to absorb the foreign particles present in the lubricant to avoid scoring and wear, [12]. As an excellent structural and functional material, the transition alloy metallic interface is of considerable importance, e.g. in quantum electronics, particularly in the context of superconducting and quantum device technologies, due to its role in enabling Josephson knots [5], superconducting qubits, quantum sensing devices, and quantum simulation platforms. Related technologies are key to the actual development of quantum computers, quantum sensors, and the advancement of quantum information science as a whole. Recently, the development of a superheated superconducting alloy metal-metal composite for granules has been used as a nuclear detector material for cold dark matter and neutrino studies [2]. Since metallic glasses interest is growing for their unique thermoplastic processing ability and excellent properties (ultra-high strength, wear and corrosion resistance, surface functionality, and soft magnetism) In this study we devised a new composite bimetal two step procedure; the first being the production of the two constituent materials as metallic glass; the second is the production and testing of laminated glass metal

II. MATERIALS AND METHOD

A. General aspects

Semimetal has a slight overlap between the conduction and valence bands; this characteristics for aluminium and tin, suggested its classification in the semimetals group. The classification justified for Al/Sn by the lack of a band gap and for having a negligible density of states at the Fermi level. A typical property in contrast of metals in that the conduction band is partially filled, [6]. In figure 1 a schematic representation shows the semimetal band structure in comparison to a semiconductor.

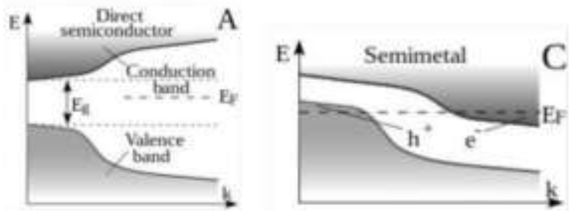

Fig. 1. schematic band structure to illustrate semimetals classification: As the right picture shows the structure has no band gap and a negligible density of states at the Fermi level, [6].

The selection on the materials used have been made on the supposition that due to the potential difference i.e. Sn (0.14 eV) and Al (1.69 eV) a photovoltaic phenomenon is expected.

Al/Sn semimetallic glass, define a material that lack a regular or a crystalline atomic structure, in opposition of that found in conventional metals. The disordered atomic arrangement in matter, similar to that of glass, shows unique properties. They typically have lower densities than crystalline metals, which can be advantageous for lightweight applications. For instance high strength and hardness, which can make them suitable for applications requiring wear resistance. Good corrosion resistance is essential for applications in harsh environments. High elastic limit allow to withstand significant deformation without permanent damage. Unique magnetic properties such as high magnetic permeability and low coercivity, making them useful in transformer cores and other magnetic applications. Good electrical conductivity favour them for electrical and electronic applications. They tend to fracture suddenly and without warning when subjected to excessive stress i.e. lack of plastic deformation before failure. Many metallic glasses have good corrosion resistance not forming grain boundaries, so no sites are formed for corrosion initiation in crystalline metals. Some alloys based on aluminium and tin have relatively good electrical conductivity. Due to their low coefficient of thermal expansion are less prone to volumetric changes with temperature variations. Soft magnetic properties, such as high magnetic permeability and low core loss, making them useful in transformers and magnetic sensors. Metallic glass have been tested also for superconductivity characteristics however so far no evidence or reports of metallic glasses made from aluminium and tin exhibiting superconducting properties at extremely low temperatures.

B. Semimetals available on the market

The exact properties of Al/Sn bMGs alloy would depend on the specific proportions of aluminium and tin and any additional elements or alloying materials used in its composition. Commercially available extrusion aluminium alloy 6061 has the following atomic composition: Iron (Fe), 0.0 - 0.70 ; Magnesium (Mg), 0.80 - 1.20 ; Silicon (Si), 0.40 - 0.80 ; Copper (Cu), 0.15– 0.40. The most popular combinations used commercially is 60% tin, 39% lead, and 1% alloys, [1]. The commercial available tin has two different composition: that employed in small technical work (Sn; 99%+Ag; 0.3% +Cu; 0.7%) and that employed for industrial product (Sn+Ag+Cu in percentage respectively 96.5%; 3%; 0.5%. Both of these materials in the form of metallic glasses, are studied to explore their potential applications and optimize their performance for the mentioned specific uses.

The compound ability to form glassy alloys is the consequence of a high configurational entropy in the liquid state, a situation that favour bypass crystallization. It is expected that heat mixing between the Al an Sn could enhance glass-forming ability. This means that the elements prefer not to mix in the solid state; for instance the mixing can hinder the formation of crystalline phases and that could be suppressed under critical cooling rate. When cooling occurred rapidly high viscosity at the liquidus temperature makes it more likely to form a glassy structure. The thermodynamic stability of the crystalline phases, if any, impede to form a bMGs. Nucleation and crystal growth during cooling could be reduced since minor elements act as good glass-forming agents. The composition range over which the alloy can form a glass is also of importance as once the glassy matter is formed, its stability at the desired operating temperature should not spontaneously crystallize during its intended application. While they are strong, they tend to fracture suddenly and without warning when subjected to excessive stress, due to the lack of plastic deformation, before failure. Nevertheless the metallic glass withstand large amounts of stress without permanently deforming or breaking, showing low deformation under applied loads.

III. EXPERIMENTAL SET-UP

Al/Sn-bMGs here are produced employing the experimental set-up based on the conceptual diagram given in figure 2.

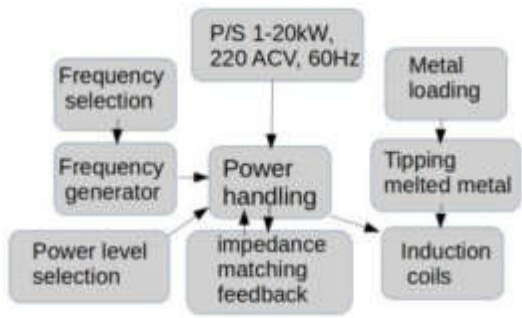

Fig. 2. Conceptual block diagram of the heath generation control and the glass metal production principle.

The block diagram provide a sintetized scheme for the Al/Sn sample rapid heating through the excited coil; the latter is reported in figure 3.

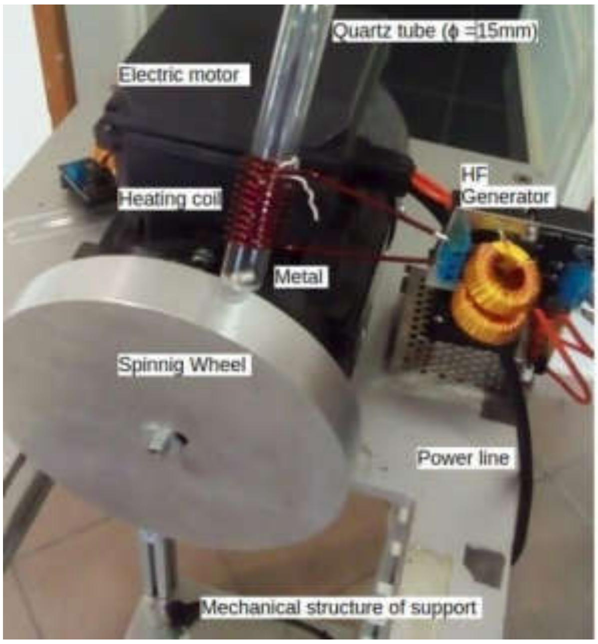

Fig.3. Picture of the power supply and the heating coil in that the bimetal is liquefied in a quartz tube. The cooling technique is obtained during the molten matter hitting the aluminium disc surface during which experiment a high rate cooling. The produced strip is released from the disc surface during wheel spinning.

The bMG sample, hitting the disc, experiments a rapid solidification trough the so called splat cooling technique or quenching. During the extremely fast cooling rate, typically on the order of millions of degrees Celsius per second, the formation of crystalline structures is prevented with the consequences mentioned. In this case atoms do not have enough time to organize themselves into a regular crystalline pattern so that the atoms bound into a disordered atomic arrays, giving the material its unique properties. The bMGs are produced by the equipment shown schematically in fig.3 and described as follows:

1. Melting the Metal: Purpose built induction furnace is employed for melting the Al/SnbMGs
2. Ejection and Rapid Cooling: Once the bimetal is in a liquid state inside a heat resistance quartz glass test tube, it is rapidly ejected onto a cold substrate to obtain a rapid solidification. The substrate on that solidification occurred, is usually a rotating aluminium metal disc with a 20 cm diameter (at 12 hundred rpm). The distance between the nozzle orifice (at the bottom of the quartz tube) and the spinning disc surface surface is 5mm.
3. Formation of thin ribbons: the quenched bimetal provide the formation of thin ribbons 300 micrometers with thickness of few hundred microns. The thickness is set by the aluminium disc diameter and rpm-value.
4. Collection: The glassy ribbons are collected and analysed to determine its properties and therefore its suitability for a selected applications.

IV. EXPECTED PROPERTIES

Glass bimetal alloys, including those composed of aluminium and tin, can exhibit a wide range of mechanical properties depending on their composition and processing methods. Here are some considerations for improving the mechanical properties of glass bimetal aluminium-tin alloys:

i.- Experimenting with different compositions we achieve a balance between strength, ductility, and other desired properties.

ii.- Trace elements in commercialized Al-Sn can enhance the mechanical properties and stability of the glass bimetal structure.

iii.- Quenching rate lead to more uniform and desirable glass metal structures, improving strength and hardness.

iv.- Annealing improve the mechanical properties since can relieve internal stresses and enhance ductility.

v.- Thinner glass metal may exhibit better mechanical properties compared to thicker ones. Thinner samples induce better structure.

vi. Smaller grain sizes in the amorphous structure can enhance mechanical properties such as hardness and wear resistance.

Mechanical testing such as tensile testing, hardness testing, and impact testing to assess the mechanical properties accurately.

Experimental Optimization: advanced materials characterization techniques, such as X-ray diffraction and electron microscopy, provide information on alloy's structure.

V. RESULTS

Typical result expected for Al/Sn(40%) glass metal alloy are given in Table 1; following range of physical properties to point toward its distinctive properties :

Table 1. Properties of bimetallic glass studied.

Physical Characte-ristics	Note	Range of values	Sources [14]
Structure	Metallic glass	Properties	[8]
Hardness	High	average hardness 24 ± 1.6 GPa	[13]
Elastic Limit	High	Elastic modulus: 71,0 GPa.	[17]
Strength	High	160 MPa; yield point: 75 MPa; relative extension: 10 %; Poisson's ratio: 0,33;	[16]
Brittle Behavior compressive strength	quite brittle	4.5 - 6 GPa	[15
Density	Lowultra dense	5.5 GPa at 850 K	[21]
Corrosion Resistance	Good		[18]
Electrical Conductivity	High	1.63± 0.02 x 10 −7 μΩ	[19]
Thermal Expansion Coefficient	Low	Constant ~ 8.24 × 10−3 /K	[11]
High magnetic permeability	low core loss	soft-magnetic properties	[10]
Superconduc-tivity	Not found yet		[22]
Other propeties	Ageing		[20]

Sn employed in the industry has the following properties: liquidus tem. 220 ºC, solidus 217 ºC . For the Al-alloys: density: 2,880 $g.cm^{-3}$; liquidus temperature: 660 degrees Celsius; solidus temperature: 557 ºC.; melting point: from 650 to 730 ºC; temperature spills: from 650 to 705 ºC; [3], [4]. Metal glassy temperature for a given set of alloys can be deduced from the following graphic given by Cao et al., [7]:

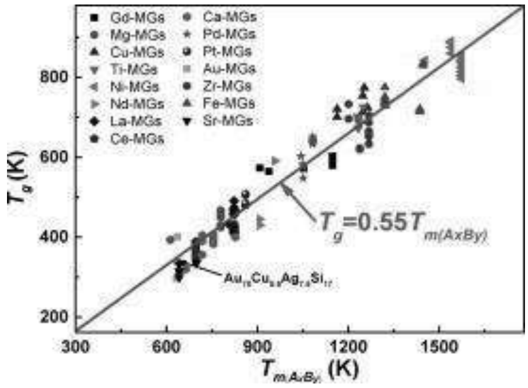

Fig. 4. Metallic glassy temperature Tg for various alloys from Cao et al., op.cit.

The next series of pictures show the metallic glass surface produced by drop cooling only.

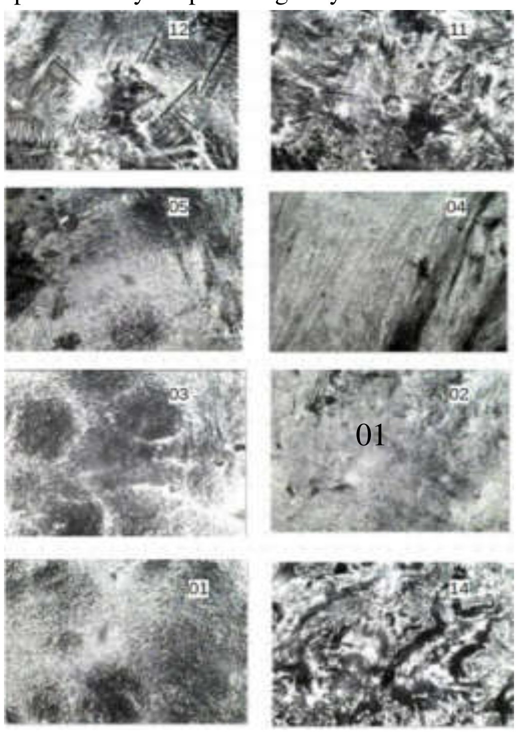

Fig. 5. Al/Sn alloy metallic glass surface microphotographs. Particularly the original images, numbers 02 and 03. clearly shows the dentritic crystallization. Pictures 04 and 05. show typical images of amorphous alloy. The others are given for analogy.

For comparison of a surface corresponding to a normal solder joint is given in figure 6, as an evidence of crystallization obtained when it cools in open air.

Fig. 6. For convenience and visual comparison we give two surfaces corresponding to a normal solder joint resulting from low cooling rate in open air, [op.cit].

An additional picture in figure 7, is given to show the dentritic crystallization shape that take place in bulk tin

Fig. 7. Surface of bulk tin that to shows typical dentritic crystallization structure obtained at a relatively low cooling rate, [9].

Figure 8 is given to show surficial structure difference between multi-MG and bi-MG.

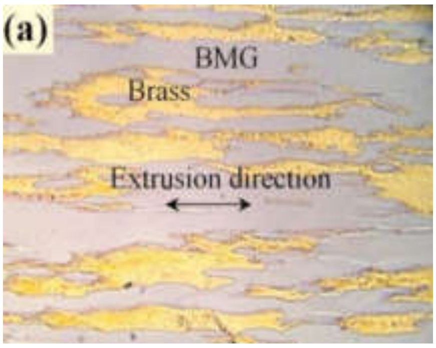

Fig. 8. Optical microphotograph of Ni (59%); Zr (20%); Ti (16%); Si (2%) Sn (3%) composite brass metallic glass surface (longitudinal section); that has an electrical conductivity of $1.63 \pm 0.02 \times 10^{-7}$ μΩ, 2.5 times higher in comparison to brass Cu (80%)+Zn (20%), [19].

Properties of bMG can vary significantly depending on their composition and processing methods, the specific temperature (Tg). Tg value can be deduced from Cao et al., op.cit.

VI. DISCUSSION AND CONCLUSION

Glass Al/Sn bimetal has been produced from liquid phase fast quenching process that lead to mechanical property; these differ from the crystallized metal structure. The bMG process improve the Sn compound strength by 25%, but at the same time ooccur at the expense of e.g. ductility. Drop cooling, in opposition of splash cooling, resulted in our case as an effective method for producing bimetallic glasses. We confirmed that the cooling rate is the most essential parameter for the sample production since properties of glassy metals vary significantly. In general term the absence of a crystalline structure gives metallic glasses some interesting properties and advantages over crystalline metals. Al/Sn bMGs exhibit to some degree excellent properties such as ultra-high strength and excellent wear and corrosion resistance. Glass metal technology leads to fundamental changes in the properties of individual metals. The basic properties of tin (Sn) and aluminium (Al) are known as metals for industrial use, as well as their alloys. Expected mechanical properties are: tensile strength: 160 MPa; yield point: 75 MPa; relative extension < 10 %; hardness 45 NV; Poisson's ratio 0,33; elastic modulus: 71,0 GPa. In the course of our research, we are looking for answers to the question of:

Achieving a balance between different properties depends on the specific application requirements. In this study it can be appreciated that a systematic approach is required to develop a glassy aluminium-tin alloys to fulfil a particular application. Additionally, research in materials science and engineering continues to evolve, so staying updated with the latest advancements in alloy development is beneficial.

i.- Al/Sn alloy glass metal - mechanical, magnetic and electrical properties, that could be useful for industrial applications can be produced ii.- Al – Sn thin-film glass metal materials could be produced as thin ribbons.

It is assumed that based on the electrochemical potential of the raw materials, the unique magnetic properties of the new types of glass metals created from them may converge towards the properties of superconducting materials, and their optoelectric properties may make these materials suitable for the manufacture of solar cells. Characterization of the Al/Sn metallic glass is under scrutiny.

In spite of limited understanding on the relationship between their atomic structure and mechanical properties as a function of their structural state, the technique with drop cooling, is adequate for bMG production. Since it is a novel materials with unique properties could spread advantageously in various ¨*high tech*¨ industries. The use of artificial intelligence predict 20,000 samples of different metallic glass alloys and so far it may be considered an open field for basic research. Authors are planning to further study both the structure characterization and properties of metallic glasses.

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