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Critical Review of Literature For Computational Investigation of Mechanical Properties of CNT Reinforced Bulk Metallic Glasses

[1] Manish Dhawan*, [2] Sankalp Sinha

[1]Associate Professor, Department of Mechanical Engineering, Lovely Professional University, Phagwara-144411, Punjab, India
[2] Research scholar, Department of Mechanical Engineering, Lovely Professional University, Phagwara-144411, Punjab, India

* Corresponding Author: E mail address:- mds_78@rediffmail.com (Dr. Manish Dhawan)

Abstract

Carbon Nanotubes are one of the toughest materials on the planet. Their strength to weight ratio is phenomenally high and this lends them to be used in a variety of reinforcement applications. In this study, we look at the effects of adding SWNT to bulk metallic glasses as a reinforcement on the mechanical properties of the material. Bulk metallic glasses or amorphous metals have a relatively low glass forming temperature and just grow stronger with decrease in temperature, which lends itself pretty well for space exploration applications. However, as is currently stands we can just produce small parts like gears and cogs due to the production process requiring extremely high rates of cooling. However, with reinforcements from SWNT we can further increase their strength and durability significantly, increasing the potential applications to a wide variety of fields.

Keywords: Molecular dynamics; Nanocomposites; Bulk metallic Glass

1. Introduction

Modern problems require modern solution is a popular term in today's culture, but never has it been truer when it comes to designing new materials for a variety of application. With advancements in technology and the rate by which we get new breakthroughs all the time, combined with the need for sustainable growth that doesn't adversely affect the environment, the need for discovering newer materials with a wide range of applications has never been higher. In today's environmentally aware culture the need for cheaper alternative materials, which are easy to produce and manufacture, is at an all-time high.

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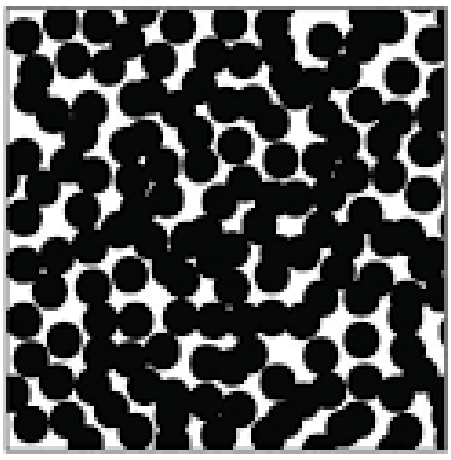
With most notable futurists agreeing that the next step for human race is space colonization, we cannot help but notice the dire need for utilizing the majorly untapped resource, which are composite materials. Composites can inherently combine the best and desirable properties of two or more materials, we get a product that is greater than the sum of its parts. It can also help compliment the weaknesses of its constituent materials. To wit, bulk metallic glass and carbon nanotubes (here forth referred to as BMG and CNT respectively) are excellent candidates for constituting a great composite, which is perfect for deep space applications as well as relatively easier to manufacture.

1.1 Bulk Metallic Glass

An amorphous metal can be defined as an alloy with disordered atomic scale structure that is metallic solids. Since the crystalline form is common in solid state of most metals. The amorphous metals form a glass-like structure. Figure 1 shows the difference between the amorphous and crystalline structure However, unlike window glass they can show good electrical conductivity. Most common methods of production include physical vapor deposition, ion-irradiation, extremely rapid cooling, solid-state reaction and mechanical alloying. When alloys with extremely low critical rates of cooling form a thick amorphous structure with layers of over 1 millimeter then it is called bulk metallic glass. Earlier than 1960 it was rarely possible to arrange the atoms of a solid in a chaotic disorderly manner like liquids, except for in form of very thin wires and ribbons that had no practical applications. In recent years advancements in the field of material science has led to development of highly resistant and durable bulk metallic glasses whose primary application right now is in mobile phones to allow them the capability of wireless charging or contact charging by eliminating eddy currents that might arise due to a metallic back panel. BMG is also lighter than metals while being just as strong thus giving us a superior strength to body ratio.



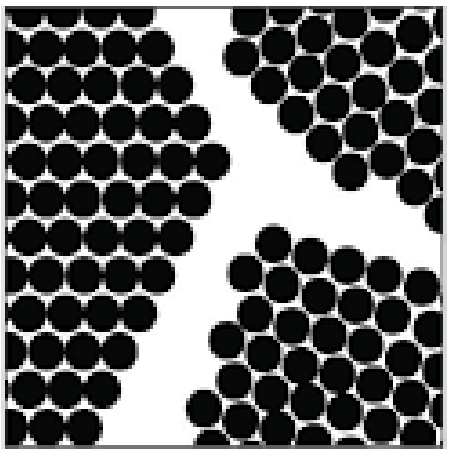


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Figure 1 Amorphous Structure Vs Crystalline Structure

1.1.1 History of Bulk Metallic Glass

The very first successful attempt at producing a metallic glass can be traced back to 1960 by W. Klement (Jr), Duwez and Williams using an $Au_{75}Si_{25}$ alloy at Caltech University [1]. Similar alloys needed to be cooled in the orders of one mega kelvin per second (10^6K/s) for them to avoid crystallization. This added the limitation of the form being limited to ribbons and wires of thickness less than one hundred micrometers.

It was not until 1988 that alloys of copper ore, lanthanum and aluminum were found to have a high glass forming ability. Al based glasses containing Scandium broke records for tensile strength at 1500MPa [2].

The decade of 1990s saw the rise of many new alloys with cooling rates as low as one kelvin per second. These "bulk" amorphous alloys contained so many different elements that if cooled quickly enough the atoms can be "confused" into arranging themselves in a non-crystalline state when the mobility stops, thus locking in the structure. Best of these were palladium and zirconium but titanium, magnesium, copper and iron were found to be suitable alternatives.

Most recently, the team at SLAC motion Accelerator Lab reported the use of Artificial Intelligence to predict 20000 different alternatives in just a year [3]. Bulk Metallic Glasses (BMGs) have been modeled using simulations in a similar way as high entropy alloys [4-5].

1.2 Carbon Nanotubes

Carbon Nanotubes (CNTs) are cylindrical nanomaterials, which are allotropes of carbon. This unique nanostructure grants it a slew of unparalleled properties, which make it valuable for optics, nanotech and microelectronics as well as making them a welcome addition to the fields of material science and technology. The most notable of these are its high tensile strength, which makes it an excellent additive to various structural materials. They have been known to be used in various products including baseball bats, car parts, golf clubs and damascus steel [6].

The Carbon Nanotubes have the unique boast of being one of the strongest materials in nature. Although the CNT have a different sets of properties in different axial and radial directions due to its geometry and nanostructure. The axial direction shows Young's modulus as high as 270-950 GPa.

A quick review of the Young's Modulus, Tensile Strength and Elongation of break reveals that Single Walled Carbon Nanotube (SWNT) with armchair configuration has the highest tensile strength thus proving to be a best fit for the purpose of our study.

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1.2.1 History of Carbon Nanotubes

Although the true identity of the discoverers of carbon nanotubes has been a controversial topic [7]. An editorial written in 2006 claimed to have solved this mystery when Marc Monthioux and Vladimir Kuznetsov [8] in the journal *Carbon* attributed the discovery of hollow carbon tubes of nano metric sizes to Sumio Iijima of NEC in 1991 [9].

A paper published in 1952 by Lukyanovich and Radushkevich showed hollow graphite carbon fibers with diameters as low as 50 nanometers. Sterling, Hofer and McCarney followed three years later in 1955 with tubular carbon filaments of 10-200 nanometers in diameter [10].

The 60s saw Roger Bacon grow "graphite whiskers" in a specially made arc-discharge apparatus and used cutting edge microscopes to study the nanostructure [11]. Bollmann and Spreadborough reported the first observation of MWNT in nature [12].

Morinobu Endo of CNRS synthesised hollow rolled graphite sheets by a chemical vapour-growth technique in 1976. This was the foundation for SWNT that we know today. The mass-produced MWCNTs today are based on the findings of endo, which garnered him the honor of the process being named "Endo-process" as a token of respect for his contributions to the field [13].

John Abrahmson was the first to present the evidence of CNT at the 14th Biennial Conference of Carbon at the Pennsylvania State University. Although these were technically carbon fibers [14].

In 1981 was the year in which soviet scientists published groundbreaking results and suggested that two possible arrangements were theorized: circular arrangement (Armchair) and a spiral one (chiral).Though it was always, the seminal publication of Iijima published in 1991 that brought the nanoparticle into mainstream science.

More recently, the research into the electro conductivity and thermal properties of carbon nanotubes have put them in the forefront of nano electronics and other fields related to nanotech. A huge research gap observed in the review has been the mechanical properties of this nanoparticle, which makes it a prime additive in nanostructures of most composites to enhance their strength and durability.

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1.2.2 CNT Nomenclature

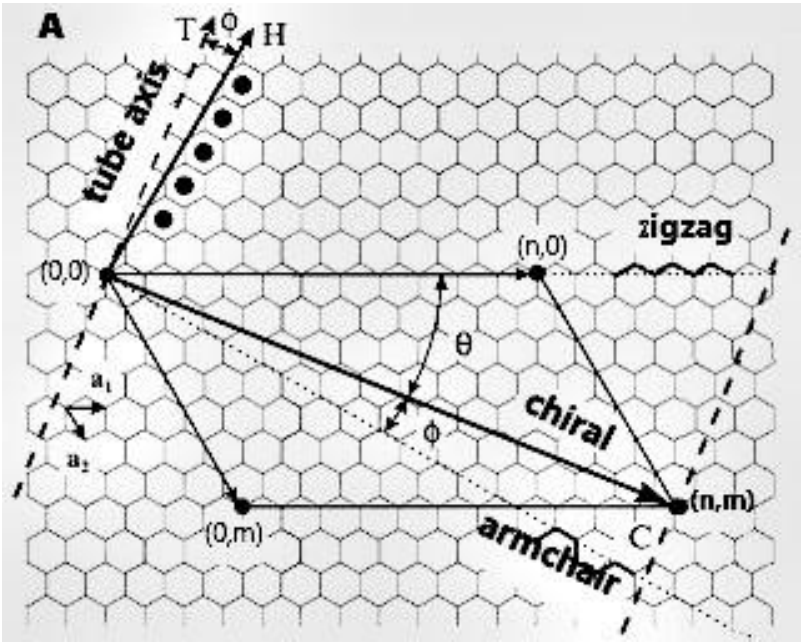

Figure 2 Graphical representation of CNT Nomenclature.

The (n,m) nanotube nomenclature can be defined as a vector (C_h) in an infinitely large graphene sheet that describes the direction in which we need to roll the sheet in order to obtain the nanotube structure.

$$d = \frac{a\sqrt{(n^2 + nm + m^2)}}{\pi} = 78.3\sqrt{((n+m)^2 - nm)}pm \quad \text{-------- (1)}$$

Where: d is the diameter of the nanotube

a_1, a_2 are the unit vectors of graphene in real space

T is the axis of the nanotube

C_h is the vector perpendicular to T given by

$$C_h = na_1 + ma_2 \quad \text{---------- (2)}$$

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SWNT can be defined as a single thin layer of graphene rolled upon itself to join at the two ends together thereby making a cylindrical nanostructure with thin single walls. This can further be subdivided into different geometries based on the direction of the C_h vector and the direction of rolling of the infinite graphene sheet has been showed in figures 3-7. This makes them a prime choice for microelectronics. SWNT can function as excellent electro conductors even at the orders of a single nanometer [15-16]. This led to its use in the world's first intermolecular logic gate in 2001 [17].

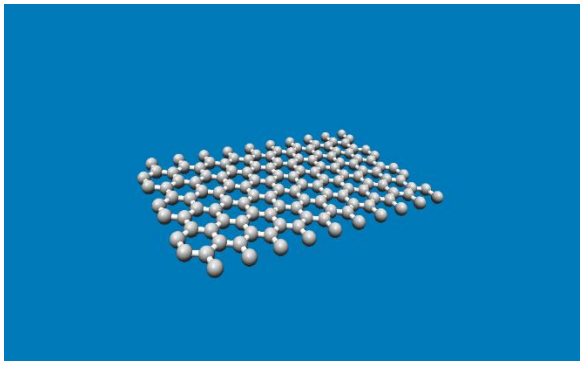

Figure 3 Graphene Sheet

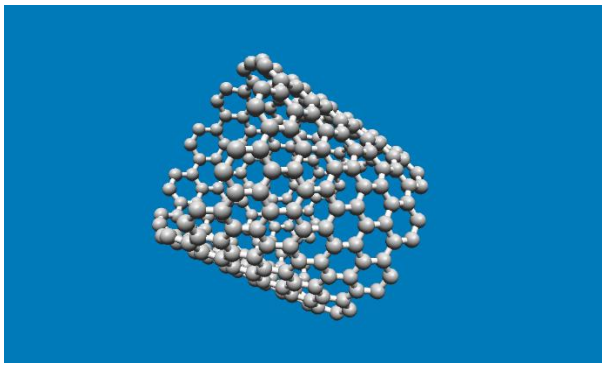

Figure i Armchair CNT

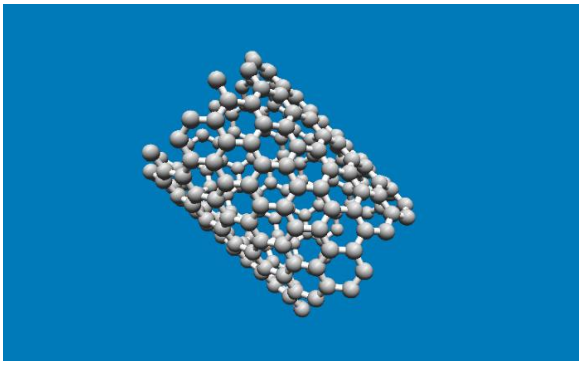

Figure 5 Chiral CNT

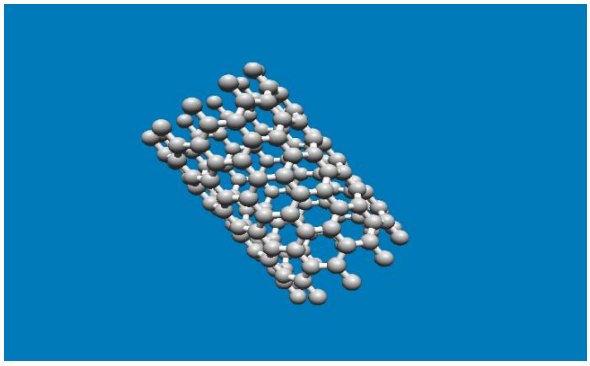

Figure 6 Zigzag CNT

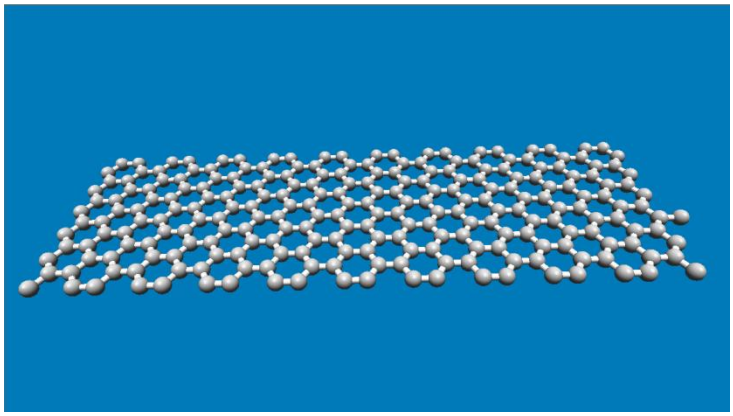

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Figure 7 Graphene Nanoribbon

We selected zirconium based bulk metallic glass reinforced with armchair SWNT as the focus of our study because of the excellent GFA of the zirconium coupled with the high tensile strength and stiffness of the armchair SWNT makes it a strong candidate for modelling and simulations.

Using the recent advancements in the modelling of BMG using artificial intelligence gives us a chance to analyse the functional mechanical properties of the CNT reinforced BMG.

2. Review of Literature

Hofer, et al.(1955) [10] **s**tudied the deposits of carbon formed on iron cobalt and nickel when carbon monoxide acts on it. They observed the deposits on iron to be composed of solid strands, while nickel had either tubular or untwisted bifilaments. Cobalt was observed to have both kinds of deposits.

Klement, et al.(1960) [1] observed that solid metals and alloys were forming thin sheets of highly disordered arrangements of atoms is obtained at extremely low temperatures but not much else. So they designed an experiment to quench Gold Silicon alloy so rapidly from the melted state that it avoids formation of the equilibrium crystalline structures. They studied the alloy by means of x-ray diffraction.

Bacon, et al.(1960) [11] grew graphite whiskers in a DC arc under 92 atms of pressure by argon at 3900K. He embedded them in a solid matrix of graphite. He observed them to have diameters ranging from a fraction of a micron to over five microns. The whiskers were shown to exhibit high flexibility, tensile strengths up to 2000kg/mm^2 and young's modulus to be over 7X1012 dyne/cm^2.

Bollmann, et al.(1960) [12] attempted to explain the mechanism behind graphite being such a good lubricant for moving parts. They rubbed powdered graphite between two glass sheets and studied then under an electron microscope. They observed that the thin layers of graphite formed rolls in places that were thin enough to observe.

Oberlin, et al.(1976) [13] Produced one of the first studies to successfully synthesize carbon fibers that took the form of multi walled nanotubes or MWNT. The used a mixture of hydrogen and benzene at 1100^{0}C and performed pyrolysis to synthesize MWNT. They then proceeded to study it’s structure under an electron microscope to draw conclusions on their newly produced fiber.

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Iijima(1991) [9] Published a seminal study on the structure of graphitic carbon fibrilis, ushering the carbon nanotubes, as they are now known, into the forefront of material science studies. He used an arc discharge method to produce carbon nanotubes on the electrode and studied it's structure.

Howard, et al.(1992) [18] filed a patent for a method of producing carbon fibrils. Their invention deposited highly ordered carbon cylinders with a distinct inner core but a substantially concentric ordered outer region.

Mintmire, et al.(1998) [15] calculated the electronic structure of fullerenes and then applied those results to an electron-lattice interaction model. They estimated the mean-field transition temperature from a Peierls-distorted regime to a high-temperature metallic regime. Such fullerenes had advantage of carrier density and band gap similar to that of metals at room temperature.

Elstner, et al.(1998) [19] successfully synthesized amorphous $Ti_{50}Cu_{28}Sn_7$ and its composites by mechanical alloying of the powered down mixture of its constituent elements. They found the metallic glass composites to attain a large supercooled liquid phase before they crystalized. On checking the thermal stability of the amorphous matrix they found it to be influenced by the presence of CNT. They also reported a nearly 30% increase in hardness at 10% CNT by volume.

Abrahamson, et al.(1999) [14] studied the structure of the thick mat of crystallites and fine fibres found on graphite and carbon anodes. They concluded that they could not have been formed by deposition after switch off instead must exist during arc operation.

Dekker (1999) [16] used the conductive properties of fullerenes to demonstrate that they are the smallest wires made yet and shows their applications in quantum computing.

Martel, et al.(2001) [17] discussed the ambipolar nature of electrical transport when CNT is used a conductor. They showed SWNT junctions to be abrupt and robust.

Bian, et al.(2002) [20] reinforced Zirconium based bulk metallic glass with CNT to produce lightweight bulk metallic glass composite that showed significant improvement in physical as well as mechanical properties when compared to undoped version of the glass.

Bian, et al.(2003) [21] used ZrC based bulk metallic glass reinforced with CNT to demonstrate that the addition of CNT to the composite made it an excellent material for wave absorption and to have strong ultrasonic attenuation. He argued the origin of these properties to the strong multi-scattering that the mixed structure of CNT and ZrC crystals produced.

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Mattren, et al.(2003) [22] Studied the inter atomic behaviour of the sample BMG using an X-ray diffraction method. they raised the temperature above the glass transition temperature for the sample and then compared the behaviour of the sample to that of super-cooled liquid and glass. they found a smooth transition through the glass transition temperature with widely different behaviorism on either side of it.

Inoue, et al.(2004) [2] studied the effect of adding Sc to aluminium based amorphous metal alloy on basic mechanical properties, glass transition behaviour, GFA and super-cooled liquid region. Their research also aimed to introduce the ultrastrong $(Al_{0.84}Y_{0.09}Ni_{0.05}Co_{0.02})_{95}Sc_5$ alloy which had the highest tensile fracture strength reported to date at the time of publishing the paper(<1500 MPa)

Wang, et al.(2004) [23] used the same composite as Bian, et al.(2003) to perfect the preparation process for the composite and then performed tests to attempt to find the physical and mechanical properties of the composite. They reported that the composite had increased fracture strength and showed Strong ultrasonic attenuation characteristics and excellent wave absorption ability.

Lee, et al.(2005) [24] studied the crystallisation kinetics of zirconium based bulk metallic glass alloy on heating. He discovered that the nucleation process was not consistent with classical nucleation theory. Their suggested solution to the problem was to substitute the nucleation rate with the number density of nuclei for the growth phase.

Wang, et al.(2006) [25] Studied the kinetics of Glass transition and crystallization in CNT reinforced Magnesium based BMG. They investigated this by using a Differential Scanning Calorimeter. The influence was shown in kinetic effect of the glass composite. Addition of CNT in the glass matrix affects the heating rate on the crystallization process. He also discusses the GFA mechanism which was decreased.

Monthioux, et al.(2006) [8] discussed the controversy surrounding the discovery of carbon nanotubes which is generally credited to Ijima in the nineties. They however make the argument that MWCNTs were shown to have been produced as early as 1976 by Oberlin et al.

Hsu, et al.(2007) [26] studied the effect of addition of CNT on the thermal stability of titanium based BMG. he obtained BMG composited discs by vacuum hot pressing process. He achieved a nearly 30% increase of BMG composite on addition of 10% CNT by volume.

Eckert,et al.(2007) [27] studied the mechanical properties of BMG composites. Their article reviewed the microstructure development, processing and resulting mechanical properties of Zr-, Ti-, Mg-, Cu- and Ni- based alloys of BMG. they considered composites to be superior in terms of enhanced strength, ductility and toughness.

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Eklund, et al.(2007) [28] conducted an international study to discuss the recent progress in the field of Carbon Nanotubes. They discuss the commercial potential according to academic, government, research and industrial facilities. They discuss the method of manufacture, equipment, processing and separation techniques in conjunction to their applications in electronic optical as well as mechanical fields.

Mendelev, et al.(2007) [29] Studied the elastic properties of binary Cu-Zr based glassy metal alloys by creating a computer model of the sample and comparing the acoustic velocities to that calculated by x-ray diffraction, they calculated the young's modulus of the alloy at different compositions and used it to find a relation between the elasticity and Cu concentration.

Hui, et al.(2007) [30] Studied the formation and structure as well as the properties of ternary Mg based BMG alloys. They preped the sample by dispersing solid Mg flakesinto the composite matrix and the followed by synthesi by comparing it's long period order structre with monolithic Mg based BMG alloys. They found that the LOS structre helped enhance the mechanical properties due to multiple shear band generation and LOS deformation.

Ritter, et al.(2007) [37] Confirmed the previous concept of internal interfaces in nanoglasses. Used a molecular dynamics simulation approach to model internal interfaces in glassy alloys and found that the interfaces helped in propagation of cracks by forming shear bands therefore decreasing the fracture strength an structural integrity of the glass.

Lee, et al.(2008) [31] Studied the phase field model of BMG for deformation that led to shear band formation and crack propagation in the composite due to presence of fibers. They discovered the crack propagation to be affected by fibers' length and orientation. They also used simulation study to corroborate their thesis and identify the different fracture modes for the composite.

Duan (2008) [32] Performed simulations on a Cu-Zr binary glassy alloys in order to study the effect of temperature, configuration and volume on the glass forming ability and the elastic properties of the material. They found cavitation occurred at high pressure which led to crack propagation and affected the elastic properties inversely.

Senkov, et al.(2008) [33] Studied the past literature on Ca based BMG to find the best possible alloying material for the best and desirable properties for low density Ca based BMG. they found that although the Ca based sample had a lower elastic moduli than other glassy alloys it could easily be solved by finding a suitable alloying metal.

Wang, et al.(2008) [34] Studied the GFA and atomic structure of Cu based BMG of two different compositions to figure out the best sample for the desired properties. Used a combination of experimental as well as computer simulations to study

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the atomic structure of both samples and concluded that the sample with higher Cu concentration had slightly denser packing and less distorted structure giving it a better GFA.

Zheng, et al.(2010) [35] Investigated the crack propagation and shear band formation in fiber reinforced BMG using a phase-field model for deformation. They embedded long ideal fibers into the BMG and then studied their effect on shear band formation and crack propagation. They found a significant increase in fracture strength on comparing with real tungsten reinforced Zr based BMG composites.

Talemi, et al.(2011) [36] used samples of CNT reinforced BMG to measure its emission performance in an electron field. Their composites were reported to be the best material for electron field emission at the time.

Gullapalli,et al.(2011) [6] Detailed a list of uses for different nano objects in their work on nanotechnology. The work included potential applications of CNT and other common nano objects. They also mentioned the use of CNT in Damascus steel to give strength to ancient swords thereby dating the use of CNT back to ancient times before the rise of technological age.

Pujadó(2012) [7] Wrote a thesis on the use of CNT as bio-sensors. He studied the excellent electro-chemical properties of CNT and used that knowledge, combined with the ability of CNT to form versatile functional bio composites, to make bio sensing devices that can be implanted into organic tissues without any harm to the patients.

Sharma, et al.(2012) [38] compared the storage moduli and loss factors for three different composites that were reinforced with fibers to show the transverse and shear properties of the reinforced nanocomposite. They showed that a staggered array arrangement of fibers gave the highest values for aspect ratio.

Garret, et al.(2012) [39] predicted the optimum composition that was required to have the highest possible glass forming ability in amorphous metals. They developed a computer based model to analyse the effect of addition of Aluminium to Cu-Zr on the glass forming ability of the alloy. The results showed that GFA depended on a combination of three governing factors namely the low thermodynamic force for crystallization, large ratios of icosahedral structures in liquid phase and a high melting viscosity.

Sharma, et al.(2014) [40] studied the effect the Stone Walves and vacancy defects has on the modulus of elasticity of CNT and its composites. Their results showed a gradual degradation of strength on increasing the defects and diameter of the armchair configuration for CNT they also found the modulus of CNTs with SW defects decreased more rapidly than CNTs with vacancy defects. The radius of the SWCNT also had an inverse effect on the modulus where transverse moduli decreased by almost half.

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Ju, et al.(2014) [41] Used SABH method with tight binding potential to predict the micro-structure of Mg67Zn28Ca5 and Ca50Zn30Mg20. They found that Mg based BMGs had predominantly perfect icosahedral micro-structure while the Ca based variant showed distorted icosahedral structure.

Sopu, et al.(2015) [42] used MD techniques to find the relation between the direction of arrangement of nanowires in a BMG composite to its deformation and how it was affected by the martensitic phase deformations. Their results showed that the composites with their nanowires in the same direction as that of the deformation showed a two-steps stress-induced martensitic phase transformation.

King, et al.(2015) [4] discussed the method of formation as well as the conditions required for the formation of thin V-Zr amorphous films. They characterized the films by X-ray diffraction, transmission electron microscopy and computational methods.

Middleburgh, et al.(2015) [5] pioneered the investigation of crystalline structures and amorphous nature of U3Si using density functional theory techniques.

Anjana, et al.(2016) [43] used Simulation study to check for the efficiency of such methods by comparing their results with past research. Their simulations showed that the results predicted by MD were in agreement with the Mori-Tanaka and Finegan models.

Choi, et al.(2016) [44] used MD simulation to study the effect uniaxial tensile loads on the CNT reinforced aluminium composite. Their results showed that the basic mechanical properties showed significant increase on doping with CNT. their simulations also offered a detailed fracture mechanism at the atomic scale.

Mahmood, et al.(2016) [45] applied molecular dynamic simulation to study the mechanical properties of CNT reinforced metallic glass nanocomposites. Their results showed a significant increase in the mechanical properties when the composite had long CNT whereas the composite with short CNT showed almost no increase in properties.

Sharma, et al.(2016) [46] Studied the effect of adding functional groups to the surface of CNT on the elstic properties of SWNT. they used carboxylic, silane, ester and vinyl groups for the study and found a significantly large decrease in the elastic moduli when compared to undoped SWNT.

Sharma, et al.(2016) [47] studied the mechanical properties of Graphene reinforced BMG as well as CNT reinforced BMG and discovered that the long Graphene/BMG had a higher increase in Young's modulus than long CNT/BMG composites for the same volume fraction. They also showed that short composites barely showed any increase in properties

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Chawla, et al.(2017) [48] Simulated the CNT pull-out to discover its effect on the properties of CNT. they found that an increase in volume fraction of an armchair SWNT resulted in reduced average energy increment. They also found a reduction in longitudinal Young's modulus when the SWNT was pulled out from the PE matrix.

Patil, et al.(2018) [49] studied the effect of coir fibers on the mechanical properties of vulcanized natural rubber composites in an attempt to predict its effect on tensile strength, elongation at break(%) and the maximum load it could take. They performed aging tests on the material and then recorded the results. The results showed the composite to outperform the base materials after each aging tests and highest increase in water aging resistance

Ren, et al.(2018) [3] discussed the impact of machine learning and high throughput experiments have on the discovery of metallic glasses. Machine learning uses self correcting codes and genetic algorithms to simulate the process of learning from mistakes over time and repeat iterations. Using these codes in conjunction with computational analysis of molecular structures we can predict more new materials with accuracy in less time.

Brink, et al.(2018) [50] Studied the deformation pattern of grain boundaries and how they are affected by cooling rates during formation and synthesis of glassy metals and alloys. They used molecular dynamic simulations for the study and found the results to divide the grain boundary patterns into three basic categories.

3. Research Gap

The review of past literature leads us to believe that extensive studies have already been conducted on the thermal, mechanical as well as electrical properties of CNT and BMG individually. However, most of these studies have either been with other materials being used for making composite samples or experimental studies. One key area that has been overlooked however, the computational study of CNT is reinforced BMG composite materials, which are some of the best when it comes to strength to weight ratio. We therefore decide to focus our efforts into studying the mechanical properties of the above-mentioned composites.

4. Observations

Our extensive review of literature gives us the following data to consider. The different manufacturing techniques currently being used for producing and testing CNT vary based on application and can be broken down into the flowchart shown in figure 8. The experimental setups require time, money, are therefore being passed over by computational, and simulation methods due their shorter turnaround time and high throughput. The same can be said for BMG as due to the manufacture of BMG requiring very high cooling rates, the sample sizes get limited to very thin and very small components. On the other hand computational methods can allow us to test and develop wide variety of different compositions for amorphous metals.

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With the latest developments in neural network algorithms and AI the turnaround time for these computational methods has decreased significantly.

Figure 8 shows the comparative strength of glassy alloys or non-crystalline metals when compared to some other commonly used materials. This clearly demonstrates that these have a very much higher strength (1500-2500 MPa) than any other material in its class all the while showing elastic limits that are comparable to most polymers (2%). Figure 9 shows that although traditional metallic glasses have a lower reduced glass transition temperature (0.4), they require unreasonably high cooling rates (10^6 K/s) which make their production almost non feasible. But modern Bulk Metallic glasses which are generally binary or tertiary in nature due to alloying composites require much lower cooling rates (~1000K/s) for a reasonably higher reduced glass transition temperature (0.6) thereby making them ideal for mass production and wide scale use.

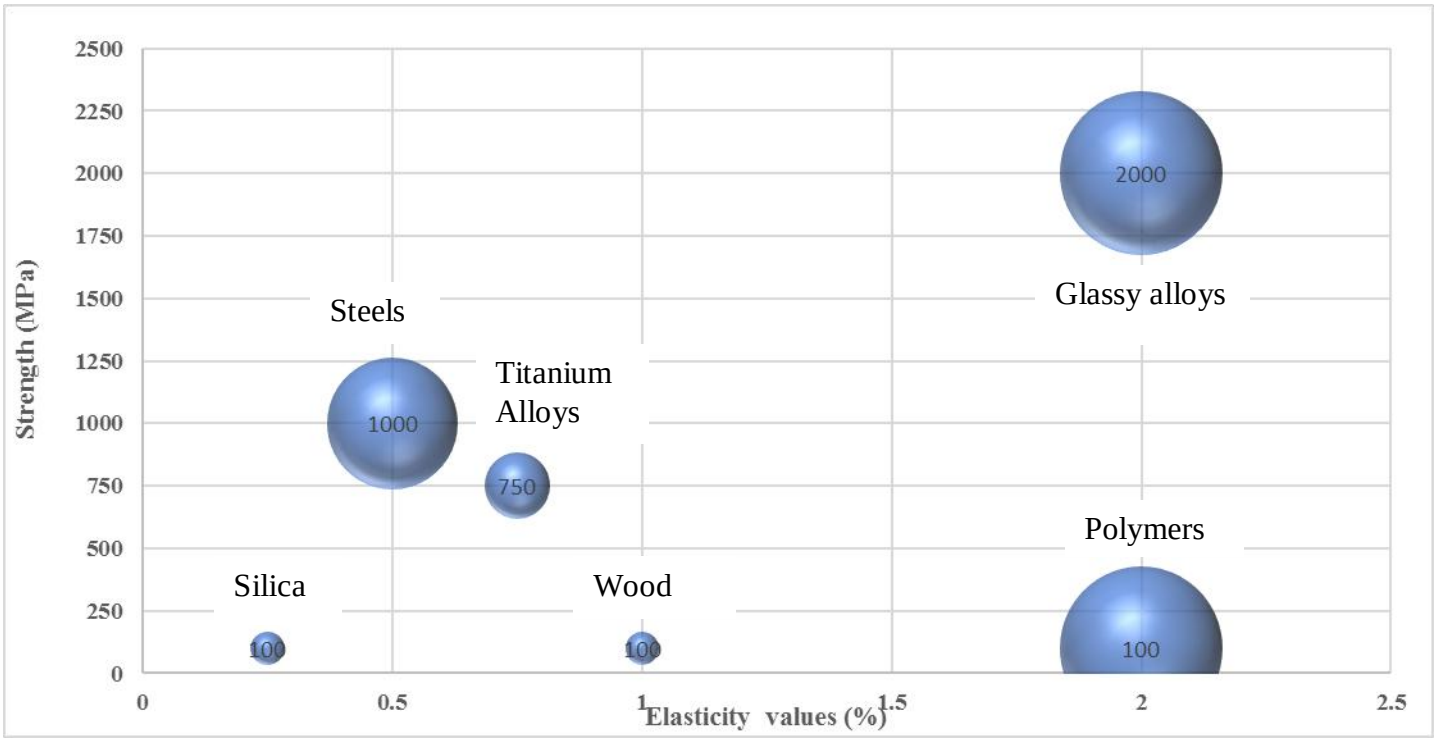

Figure 9 Comparative Strength and Elasticity of different materials

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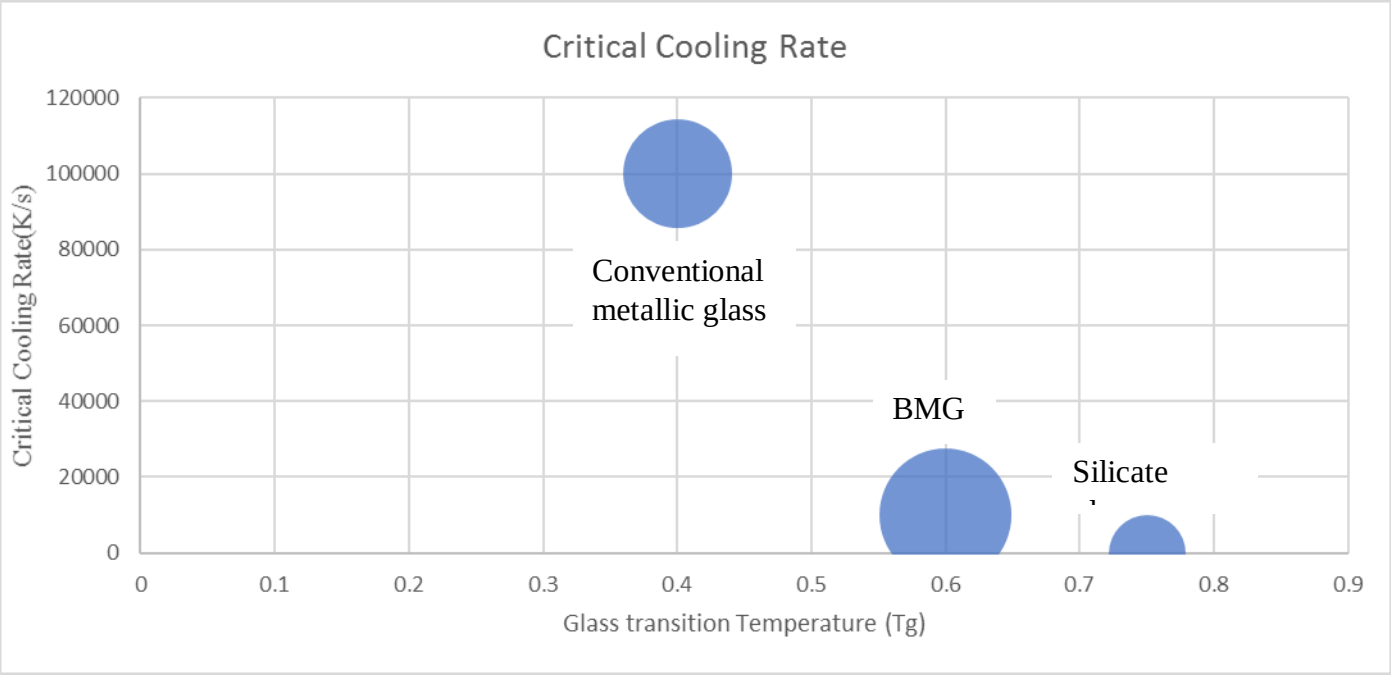

Figure 10 Comparative Cooling rates for different glasses in relation to Tg

5. Conclusion and Summary

Looking at the data, we can fairly conclude that BMG has a much higher strength and resistance to fracture than most steels and still have an elasticity comparable to most polymers. This fact when combined with the low melting temperature means it is easier to manufacture too. It gets stronger as the temperature drops which makes it an excellent candidate for application in deep space exploration.

The only drawback of the manufacturing process for BMG is that it requires very high cooling rates (~1000K/s) we can only manufacture it currently in small parts such as gears and other small components.

However reinforcing it with a mesh embedded inside it will help us achieve the same tensile strength with an even increased structural strength allowing us to manufacture larger slabs of the material that can be used in a wide variety of situations such as making shielding for space crafts during deep space exploration as well as benign applications such as shatterproof windscreens in vehicles as well as phones.

The best possible way of reinforcing BMG is with help of CNT as it has extremely small particle and fibre size as well as very high tensile strength. CNT is already used in a variety of reinforcement applications ranging from structural supports in racing cars to supporting the neck of a humble guitar. So it makes sense to use this lightweight and strong material as reinforcement for BMG.

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