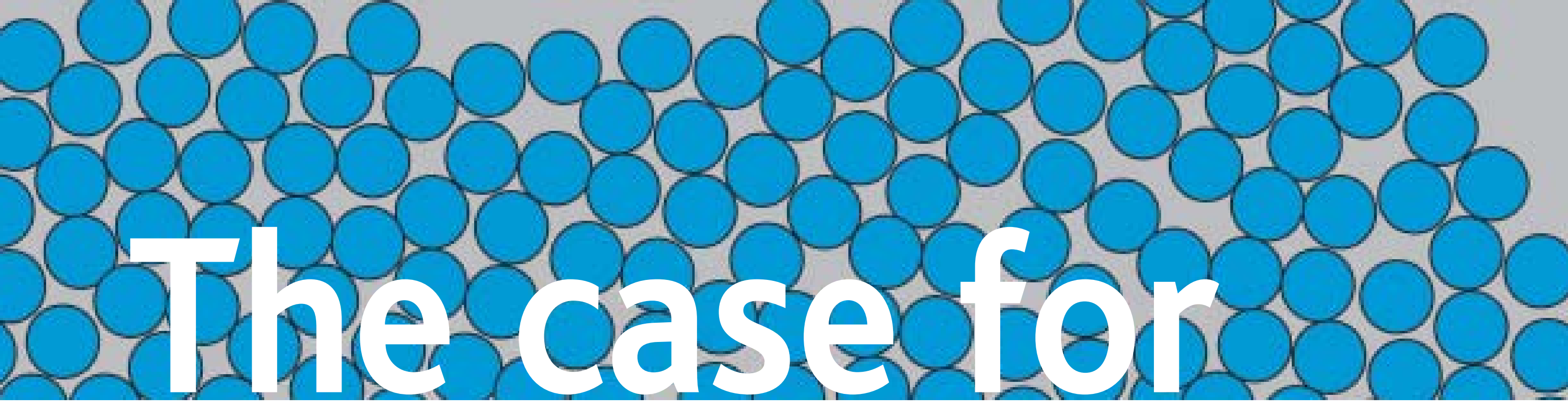

The case for bulk metallic glass

by Mark Telford

The last ten years have seen the discovery of amorphous metal alloys that are glass forming at cooling rates as slow as 1°C s^{-1} to 100°C s^{-1} in the bulk via conventional metal processing such as casting, but with the ease of molding of polymers. They are twice as strong as steel, have greater wear and corrosion resistance, are tougher than ceramics, and yet have greater elasticity. Increased plasticity in amorphous/crystalline composites now promises new structural applications.

When a conventional metal or alloy cools from the liquid melt, equilibrium is reached when it solidifies into the lowest energy state structure, i.e. a crystalline lattice. Practical metals take advantage of the highly unstable metallic liquid and crystallize just under the melting point in microseconds. But rather than forming a perfect single crystal, most metals are polycrystalline, with grains of varying shapes and sizes. Grain boundaries represent weak spots of less than optimal atomic packing, where fractures can form and corrosion starts. Misaligned planes of atoms, under sufficient stress and heat, slip past each other easily, allowing dislocations to move. As a result, metals have a much lower strength than their theoretical maximum and, since energy goes into moving atoms out of the way, deformation is plastic and permanent.

In contrast, a glass has such slow crystal nucleation and growth kinetics that the liquid can be undercooled far below its melting point before a glass transition is reached, 'freezing' as a vitreous solid without crystallizing. The atoms retain an amorphous distribution (i.e. random packing with no long-range order). However, glass is brittle.

Conventional metallic glass

At California Institute of Technology (Caltech) in 1960, Pol Duwez *et al.*[1] discovered that if a molten metal (specifically, the binary metallic alloy $Au_{80}Si_{20}$) is undercooled uniformly and rapidly enough, e.g. at 1 x 10^6 °C s^{-1}, the heterogeneous

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atoms do not have enough time or energy to rearrange for crystal nucleation. The liquid reaches the glass transition temperature, T_g, and solidifies as a metallic glass. It is less brittle than oxide glass and looks like a metal – opaque, gray, shiny, and smooth (Fig. 1).

In the tightly packed glassy structure, the displacement of atoms (e.g. to accommodate a dislocation) is obstructed. A metallic glass, therefore, absorbs less energy upon stress-induced deformation through damping and returns more by rebounding elastically to its initial shape. With no crystal defects, mechanical properties combine to produce a material with the following properties:

- Strength (twice that of stainless steel, but lighter);
- Hardness (for surface coatings);
- Toughness (more fracture resistant than ceramics); and
- Elasticity (high yield strength).

The absence of grain boundaries means that the material is resistant to corrosion and wear, as well as possessing 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 allows lower losses in applications, operation at high temperatures with minimal flux density reduction, and annealing.

Critical casting thickness

Heat conduction is slow in these materials, however, so that the requisite cooling rate can only be achieved for a very small critical casting thickness. This precludes bulk molding and, therefore, structural applications.

High velocity oxygen fuel (HVOF) thermal spraying applies low-friction, high-hardness surface coatings to make materials such as Fe, Al, and Ti corrosion-, wear-, and heat-resistant in harsh applications such as marine equipment, drilling machinery, and pipes. Coatings get harder, slicker, and more wear-resistant with use. Surface hardness is 10-20% greater than electroplated chrome. Thermal expansion is similar to steel, giving high resistance to thermal and load cycling.

In the 1970s, AlliedSignal developed another means of forming metallic glass. Molten Fe–Ni–P–B is poured onto a spinning casting wheel to produce a continuous ribbon tens of microns thick. This process was commercialized as Metglas in the early 1980s for magnetic applications such as low-loss power distribution transformer cores. Alternatively, droplets are quick-frozen onto a cold surface by splat cooling.

Fig. 1 A sample of Liquidmetal Technologies' Zr-based metallic glass.

However, to enable bulk molding, the focus has been on slowing cooling rates to increase the critical casting thickness.

Glass-forming criteria

The key empirical criteria for slow crystallization kinetics and, therefore, a stabilized supercooled liquid state and high glass-forming ability, include:

- Multi-component alloys of three or more elements: increased complexity and size of the crystal unit cell reduces the energetic advantage of forming an ordered structure of longer-range periodicity than the atomic interactions;
- Atomic radius mismatch between elements, $\Delta r/r$, greater than 12% leads to a higher packing density and smaller free volume in the liquid state compared with metallic melts, and requires a greater volume increase for crystallization;
- Negative heat of mixing between the main elements increases the energy barrier at the liquid-solid interface and decreases atomic diffusivity (increasing the equilibrium melt viscosity to three orders of magnitude greater than binary alloys); this retards local atomic rearrangements and the crystal nucleation rate, extending the supercooled liquid temperature range;
- Using an alloy composition close to a deep eutectic forms a liquid stable at low temperatures.

Slower crystallization allows a decreased critical cooling rate and enables stable bulk metallic glass formation and fabrication by conventional casting techniques.

Bulk metallic glass scales up

In 1969, Chen and Turnbull[2] formed amorphous spheres of ternary Pd-M-Si (with M = Ag, Cu, or Au) at critical cooling

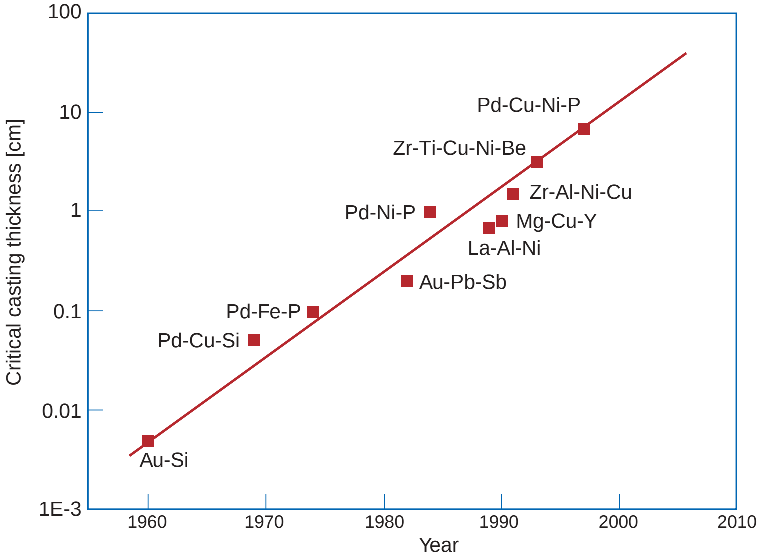

Fig. 2 The critical casting thickness versus the year in which alloys were discovered. Over 40 years, the critical casting thickness has increased by more than three orders of magnitude[6]. (© 2003 Elsevier Ltd.)

rates of 100°C s^{-1} to 1000°C s^{-1}, specifically $Pd_{77.5}Cu_6Si_{16.5}$ with a diameter of 0.5 mm. In some Pd-Cu-Si and Pd-Ag-Si alloys, the supercooled liquid range (between the crystallization and glass transition temperatures) was extended to 40 K, enabling the first detailed studies of crystallization in metallic glasses. In 1974, Chen obtained a critical casting thickness of 1 mm in Pd-*T*-P (*T* = Ni, Co, Fe)[3] and a slightly greater thickness with $Au_{55}Pb_{22.5}Sb_{22.5}$ in 1982[4]. In the early 1980s, Turnbull's group produced glassy ingots of $Pd_{40}Ni_{40}P_{20}$ with a diameter of 5 mm using surface etching followed by heating and cooling cycles. By processing in a boron oxide flux, they increased critical casting thickness to 1 cm – the first bulk metallic glass (BMG)[5]. An overview of critical casting thickness and the date of discovery is shown in Fig. 2. Progress has been significant and is outlined below.

Since the 1980s, Akihisa Inoue, of Tohoku University's Institute for Materials Research, and William L. Johnson of Caltech have discovered strongly glass forming multi-component La-, Mg-, Zr-, Pd-, Fe-, Cu-, and Ti-based alloys with large undercooling and low critical cooling rates of 1°C s^{-1} to 100°C s^{-1}, similar to oxide glasses. These properties allow an increase in time (from milliseconds to minutes) before crystallization, enabling a greater critical casting thickness (>1 cm) by conventional molding.

In 1988, Inoue discovered that La-Al-*TM* (*TM* = Ni, Cu) is highly glass-forming while investigating the mixing of rare-earth materials such as lanthanides with Al and ferrous metals. Using Cu molds, they cast glassy $La_{55}Al_{25}Ni_{20}$ up to 5 mm thick and, in 1991, glassy $La_{55}Al_{25}Ni_{10}Cu_{10}$ up to 9 mm thick[7]. Mg-*TM*-Y was also shown in 1991 to have high glass-forming ability in the form of $Mg_{65}Cu_{25}Y_{10}$[8]. An extended supercooled liquid region (to 127 K)[9] was achieved for Zr-Al-Ni-Cu, with a critical casting thickness of 15 mm[10] for $Zr_{65}Al_{7.5}Ni_{10}Cu_{17.5}$. Caltech's Johnson and Peker developed a pentary alloy based on Zr-Ti-Cu-Ni-Be in 1992[11], $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$, as part of a US Department of Energy and NASA funded project to develop new aerospace materials. With critical casting thickness of up to 10 cm possible in silica containers, the alloy became known as Vitreloy 1 (Vit1), the first commercial BMG. Variants include Vit2 ($Zr_{46.75}Ti_{8.25}Cu_{7.5}Ni_{10}Be_{27.5}$). More recently, Kündig at ETH Zürich has been investigating Zr–Ti–Cu–Ni–Al alloys[12], focusing on those similar to Vit105 ($Zr_{52.5}Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$) – one of the best glass-forming alloys.

Under the auspices of a three-year European RTN Network on bulk metallic glasses[13], which concluded in April 2003, groups at the Institut National Polytechnique de Grenoble, the Leibniz Institute for Solid State and Materials Research Dresden, European Synchrotron Radiation Facility, the Institute of Metallurgy and Materials Science in Krakow, Universidad Complutense Madrid, Universitat Autònoma de Barcelona, and the Universities of Cambridge, Sheffield, Ulm, and Turin collaborated on the development of Zr-, Mg-, Fe-, Al-, Pd-, Hf-, and Nd-based alloys. Research aimed at increasing the concentrations of light elements such as Ti, Al, and Mg in environmentally safe, Be-free Zr-based alloys.

Commercial Zr-based BMG

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

Compared to crystalline steel and Ti alloys (Table 1 and Fig. 3), Zr-based glasses have similar densities but high Young's modulus (96 GPa) and elastic strain-to-failure limit (ε_{el} = 2%). The glasses have high tensile yield strength (σ_y = 1.9 GPa), i.e. a high strength-to-weight ratio, making them a possible replacement for Al, but with a much greater resistance to permanent, plastic deformation (i.e. fracture toughness K_{1c}). Less absorption and greater rerelease of energy, i.e. low damping, means that even after high load and stress deformation the material springs back elastically to its original shape. This shape memory ability enables the use of the material in applications such as sporting equipment.

Processing: near net-shape fabrication

Above T_g in the supercooled liquid regime, Zr-based metallic glass remains stable against crystallization and softens into a liquid orders of magnitude more viscous than molten metal. This behavior, which makes it malleable at ~400°C compared with over 1000°C for steel, is more like a thermosetting polymer than a metal. This allows shaping and forming by thermoplastic processing as easily and cheaply as polymers and, hence, high-volume production with a critical casting thickness of up to 10 cm.

Unlike die-cast metals, low shrinkage during solidification allows molding of intricate, near net-shaped parts with microscale precision. The surface finish is smoother, shinier, and more consistent, eliminating most costly secondary finishing processes and allowing reuse of the mold.

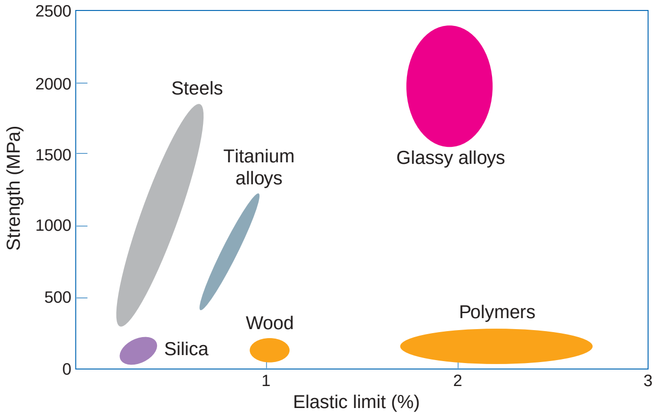

Fig. 3 Amorphous metallic alloys combine higher strength than crystalline metal alloys with the elasticity of polymers.

Deformation, flow, and shear bands

Casting in bulk has enabled the assessment of fracture and fatigue properties. Compared to polycrystalline metals with similar properties, amorphous metals are weakened at high temperatures and suffer cyclic fatigue from repeated stress. Since BMGs have high elasticity and low plasticity, they exhibit little plastic deformation prior to catastrophic failure, which limits industrial and structural applications where reliability is critical (e.g. automotive and aerospace).

Particularly at high strain rates in tensile loading, amorphous metals are susceptible to plastic deformation associated with highly localized, inhomogeneous flow, which forms intense shear bands at stress points. Because of the lack of grain structure, as well as the tendency towards strain-induced work-softening rather than work-hardening, low overall plasticity leads to low resistance to shear band propagation. This susceptibility to cyclic fatigue leads to

Table 1 *Properties of Vitreloy compared to metal alloys.*

Properties	Vit1	Al alloys	Ti alloys	Steel alloys
Density (g cm^{-3})	6.1	2.6-2.9	4.3-5.1	7.8
Tensile yield strength, σ_y (GPa)	1.9	0.10-0.63	0.18-1.32	0.50-1.60
Elastic strain limit, ε_{el}	2%	~0.5%	~0.5%	~0.5%
Fracture toughness, K_{1c} (MPa $m^{1/2}$)	20-140	23-45	55-115	50-154
Specific strength (GPa g^{-1} cm^{-3})	0.32	<0.24	< 0.31	<0.21

crack growth, fracture, and, ultimately, catastrophic failure. To obtain more tolerance to damage and enable structural use, mechanical properties need to be enhanced by controlling shear band formation and propagation.

Composites for enhanced plasticity

Obstructing shear band propagation can distribute plastic deformation and alleviate the inherent limitations of amorphous metallic glass. Increasing fracture toughness can be achieved by forming a composite alloy with a two-phase microstructure: an amorphous-phase BMG acts as a matrix for a ductile crystalline-phase reinforcement material. The reinforcement can be either extrinsic (metal or ceramic fibers or particles) or intrinsic (*in situ* precipitation of β-phase Ti dendrites from the melt during cooling, yielding partial crystallinity). The second-phase reinforcement acts as a 'crack-stopper' by adding impediments to shear band propagation[14]. The two-phase composite combines the high strength of an unreinforced, single-phase monolithic BMG with the advantages of crystallinity: increased ductility, fracture toughness, and plastic strain-to-failure[15].

Johnson has investigated a composite of Vit1 reinforced with carbon fiber[16] and $Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$ reinforced with a ductile metal wire/particulate such as W[17]. In 2000, Inoue produced nanocomposites with improved plasticity up to 2.5% by annealing glassy precursor alloys. In contrast, Johnson enhanced plasticity of BMGs without additional annealing steps by including *in situ* ductile phase dendrite dispersions[18]. They found that, upon cooling, $Zr_{56.2}Ti_{13.8}Nb_5Cu_7Ni_{5.5}Be_{12.5}$ precipitates a high-temperature, micron-sized ductile β-ZrTi (body-centered cubic) phase, which shifts the remainder of the composition closer to Vit1. Adding Nb stabilizes the bcc over the α-ZrTi (hexagonal close packed) phase. The overall (tensile and compressive) plastic strain is about 5%.

As part of the European RTN network, Kühn found that $Zr_{66.4}Nb_{6.4}Cu_{10.5}Ni_{8.7}Al_8$ forms dendritic bcc phase precipitates *in situ* during Cu mold casting. Upon annealing, the first exothermic transformation of the material is related to precipitation of an icosahedral phase from the glassy matrix[19].

In addition to Zr-based composites, others have been investigated. For example, He *et al.* modified a glassy $Ti_{50}Cu_{23}Ni_{20}Sn_7$ alloy by replacing 40% with Ti_3Ta or Ti_3Nb, where Ti and Ta (Nb) are completely miscible with each other, to obtain an *in situ* Ti-based composite consisting of ductile β-Ti(Ta, Sn) dendritic precipitates in a nanostructured matrix[20]. The material exhibits up to 14.5% compressive plastic strain, which makes structural application more likely.

Investigating structural applications

Composite or bulk metallic glasses that are lightweight and inexpensive (e.g. Al-based alloys to replace Ti) are being developed for structural applications by multi-institution US Department of Defense (DoD) programs, including:

- A team at the Center for Science and Engineering of Materials led by Caltech's Johnson, is investigating the processing, microstructure, and mechanical behavior of $Zr_{56.3}Ti_{13.8}Cu_{6.9}Ni_{5.6}Nb_{5.0}Be_{12.5}$ and other two-phase alloys. Johnson has pioneered the *in situ* transmission electron microscopy (TEM) of shear band deformation[21]. By modeling the observed patterns (using finite element analysis of hard particles embedded in a matrix), he has established the temperature dependence of the transition from homogeneous flow at low strain rates near or above T_g to inhomogeneous, shear band mediated plastic deformation at lower temperatures and high strain rates.
- The Defense Advanced Research Projects Agency (DARPA) is sponsoring a three-year, $10 million program, Structural Amorphous Metals, to develop low-cost, environmentally benign manufacturing of corrosion-resistant, reduced-magnetic-mass hull materials; moderate temperature, lightweight Fe, Al, Ti, Mg, and refractory metal alloys for aircraft and rocket propulsion; and wear-resistant machinery components for vehicles with increased life-span, durability, performance, and reduced maintenance.

Subprograms focused on lightweight structural materials include:

- The Caltech Center for Structural Amorphous Metals, established in 2001, is developing refractory and lightweight Mg- and Al-based alloy glasses and composites. Case-Western Reserve, Northwestern, Oregon State, Stanford, Michigan, and Wisconsin Universities, along with Georgia Institute of Technology, are involved.
- Structural amorphous Al for aerospace applications (to replace Ti) is being investigated by the Universities of Virginia (materials discovery) and Connecticut (process development), Pratt & Whitney (materials characterization and design), and Boeing (applications). First-generation alloys based on refractory metals, lightweight amorphous

alloys, and composite materials with an amorphous alloy matrix have a tensile strength 25% greater than commercial Al alloys.

- Work on advanced Al structural materials via metallic glass processing aims to produce components with isotropic properties and high structural efficiency for the US Air Force.

Other subprograms aim to exploit deformation and fracture at high strain in high-density composites:

- Atakan Peker of Liquidmetal Technologies is focusing on refractory amorphous metals and composites such as *in situ* W-reinforced composites for environmentally benign armor-piercing kinetic energy penetrators (KEPs). Properties include (i) localized adiabatic shear bands at high strain rates to improve perforation and (ii) high strength to survive launch.
- A project led by Texas A&M University is also developing high-density amorphous metal matrix composites for KEPs. Their approach is based on the consolidation of Zr-based amorphous metal and crystalline phase powder (or ZrC, Ta, and W) by warm equal channel angular extrusion (ECAE) into a continuous matrix phase that is close to theoretical density and has high-strain-rate failure characteristics.

A variety of uses

Liquidmetal Technologies, which was cofounded in 1987 as Amorphous Technologies International with Caltech's Johnson as vice chairman and Peker as vice president, was the first company to produce amorphous metal alloys in viable bulk form. With an exclusive worldwide license for Vitreloy (also known as 'Liquidmetal'), principal areas for products are sports and luxury goods, electronics, medical, and defense.

Golf club heads

The first application to be found 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, enabling various shapes and sizes of head. In 1997, a subsidiary was established to make clubs, Liquidmetal Golf, with heads fabricated by Howmet Metal Mold using an adapted vacuum die casting process. High production costs (e.g. to drill holes, laser in scorelines, bend the clubs, and get paint to stick), however, led to Liquidmetal Technologies terminating manufacture in favor of licensing the technology to established club makers.

Making the case for consumer electronics

Vitreloy can also yield stronger, lighter, and more easily molded casings for personal electronic products. In September 2002, at a new $45 million factory in Pyongtaek, South Korea, Liquidmetal began making components for liquid crystal display casings on cell phones. But, again, costs became a problem. "Manufacturing process limitations, higher-than-expected production costs, unpredictable customer adoption cycles, short product shelf-life, and intense pricing pressures have made it difficult to compete profitably in this commodity-driven market," explains chairman and CEO John Kang. "Processes are not yet refined to the point that we can cost-effectively manufacture price-sensitive, commodity products. Our core competency is alloy development." The company is now focusing on manufacturing select, higher-margin cell phones (mainly for Samsung) and value-added sports and medical products, as well as development and prototyping. Rather than manufacture itself, Liquidmetal Technologies is pursuing funded strategic partnerships, technology licensing, joint development, and product distribution relationships for more rapid and effective commercialization of new products.

Liquidmetal Technologies' casings have now been chosen by OQO, Inc. for its 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 Ideo 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. Last May, it teamed with Rawlings Sporting Goods Company, Inc. to produce baseball and softball bats featuring its technology (Fig. 4). In July last year, HEAD launched a range of $200-250 tennis rackets that use

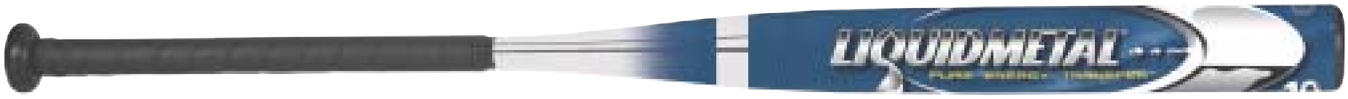

Fig. 4 Baseball bat featuring Liquidmetal Technologies' 'Pure Energy Transfer' technology based on Vitreloy.

Fig. 5 *A HEAD Radical tennis racket, which incorporates Liquidmetal Technologies' Vitreloy technology in the frame, in the hands of Andre Agassi.*

Vitreloy in four areas of the frame. The increased stiffness enhances energy return with 29% more power, it is claimed. Now used by Andre Agassi, the 'Radical' model was named one of the best new products of 2003 by *Fortune* and *BusinessWeek* magazines (Fig. 5). Liquidmetal Technologies is now working with HEAD on skis and snowboards. 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. Two years ago, Liquidmetal Technologies teamed up with the watch and jewelry division of LVMH, whose luxury watchmaker TAG Heuer launched a special edition Microtimer Concept Watch last April featuring Vitreloy as the scratch- and dent-resistant, high-gloss, casing.

Medical applications

As well as industrial powders and smooth, hard coatings, Vitreloy has a highly biocompatible, nonallergenic form, which is ideal for corrosion- and wear-resistant medical applications. For example, DePuy Orthopaedics, Inc. is using the material in knee-replacement devices. Other applications include pacemaker casings.

In 2002, Surgical Specialties began producing ophthalmic scalpel blades using Vitreloy. They are higher quality but less expensive than diamond, sharper and longer lasting than steel, and more consistently manufacturable, since they are produced from a single mold (with microscale casting accuracy) ready for use. Other edged tool applications include knives and razor blades.

Catching solar wind

As part of NASA's Discovery Program, August 2001 saw the launch of the $200 million Genesis spacecraft (Fig. 6a) with the aim of collecting samples of solar wind[22]. Orbiting the Lagrange point, Genesis is expected to capture 10-20 µg of solar wind particles and ions using five, 1 m diameter circular passive collector arrays. Each array consists of 55, 10 cm hexagonal tiles and one is coated with Zr-Nb-Cu-Ni-Al (formulated by Charles C. Hays at Caltech and prepared with Howmet's George Wolter), which absorbs and retains noble gases He and Ne (Fig. 6b).

Once the collectors are back on Earth, acid etching techniques developed at the University of Zurich will be used to dissolve the surfaces evenly, allowing captured ions to be released layer by layer. Higher-energy ions blast further into the surface. "This allows us to test proposals that [higher-energy ions] differ in composition from the solar wind," says Don Burnett, Caltech principal investigator and team leader.

Defense and aerospace

Liquidmetal Technologies has received a series of contracts from the DoD to develop military materials that are stronger, lighter, and more effective at high temperature and stress. This includes various contracts over the past five years related to environmentally benign, *in situ* W-reinforced BMG-composite KEPs. These 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 sheer away under dynamic loading, explains Todd C. Hufnagel of The Johns Hopkins University. In addition, Liquidmetal Technologies now has a $3 million, 16-month contract to develop KEPs for the US Air Force's tank-killing A-10 'Warthog' ground-attack aircraft.

The company is also finalizing a Small Business Innovative Research contract with the US Navy on casings for lightweight fragmentation bombs. Meanwhile, Liquidmetal Technologies is working with Lockheed Martin Missiles and Fire Control on a one-year program to develop lighter and stronger ceramic-BMG composite armor tiles.

Fig. 6 (a) Artist's impression of the Genesis spacecraft in collection mode, opened up to collect and store samples of solar wind particles. The cover of the canister contains one collector array and the body of a stack of four arrays that can be rotated out when the spacecraft begins its orbit. (b) Genesis' array, held by Andy Stone of the Jet Propulsion Laboratory, showing the collector materials. [(a) courtesy of JPL; (b) courtesy of NASA Johnson Space Center.]

Cheaper, easier manufacturing

There are good prospects for BMG materials whose properties favor easier, cheaper processing for more common-place applications. For example, a five-year project funded by the Japanese government between 1997-2002 (Inoue Supercooled Liquid Glass Project) reported the first bulk glassy alloy with tensile strength over 2 GPa (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[23]. Anomalies in the Cu-Zr-Ti alloy include:

- High glass-forming ability despite a small supercooled liquid region before crystallization, enabling easier casting compared with alloys with less glass-forming ability;
- A combination of high strength and ductility, even in a mixed structure of glassy and nanoscale crystalline or quasicrystalline precipitates in the as-cast state, without subsequent annealing steps.

Inoue is now leading a five-year project on metallic glasses funded by the Japanese New Energy and Industrial Technology Development Organization, which will be completed in April 2007.

This promising work, together with developments in the US and Europe, greatly improves the prospects for the discovery of new BMGs with properties that will enable practical manufacturing. In turn, this is likely to open up a new sphere of potential applications. MT

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