

Bulk metallic glasses*

The International Workshop on 'Bulk Metallic Glasses: Science and Technology' organized recently had 28 internationally renowned experts from nine nations delivering lectures. The topics covered included conceptual fundamentals as well as innovative research on different facets of bulk metallic glasses (BMGs) such as processing, alloy design principles for better glass forming ability (GFA), structures, stability, deformation, fatigue and fracture as well as applications. In addition to the invited speakers, the workshop had about 70 delegates; 21 of these presented their work as posters. Details of the workshop and abstracts of the papers can be found in the website: <http://materials.iisc.ernet.in/~bmg2007/>. Here we highlight some of the important issues which were discussed during the meeting.

The workshop started with the lecture by A. L. Greer (UK), who reviewed the brittleness aspect of metallic glasses (MGs) and the importance of the ratio of shear and bulk moduli (also expressible in terms of Poisson ratio) for selecting glass composition to optimize mechanical properties. It was pointed out that the key issue of MG is the lack of tensile ductility arising from work-softening caused by the formation of shear bands, which are highly localized into 10–20 nm thick regions. Manipulations of shear bands were found to be essential to enhance the toughness of these materials. M. Atzmon (USA) reported on the formation of shear bands in Al-based MGs during bending and indentation tests. It was shown that cold-rolled MGs did not display any new shear bands during low-rate indentation. However, on further annealing new shear bands and pile-up were observed. Though these observations were discussed using the 'free vol-

ume' model of glass, it was pointed out that structural changes which occur in shear bands during deformation are difficult to characterize and are still a subject of controversy. A. R. Yavari (France) discussed in detail the serrated or jerky flow in MGs. It was shown that in some MGs shear-band formation leads to immediate shear-off and failure, with no macroscopic plastic deformation. It was demonstrated that the formation and operation of individual and multiple shear bands in MGs led to load drop similar to Portevin–Le Chatelier effect in crystalline materials, but through different mechanisms. C. S. Schuh (USA) presented some interesting results on mechanical properties of BMG matrix composites, which represent a new class of materials exploiting an important strategy to approach the toughness and ductility problem in MGs. In La-based and Zr-based BMG composites, by controlling the reinforcements, the suitable mechanical property can be attained. V. Keryvin (France) discussed various aspects of pressure dependence on mechanical properties by indentation of BMGs. Molecular dynamics as well as finite element simulations were carried out to understand the results. Pressure-sensitivity effects were elaborated with emphasis on load–displacement curve, indentation impression morphology, hardness values, flow mechanisms underneath the indenter and fracture criteria. D. H. Kim (Korea) presented results on phase separation in (Ti,Zr)–Y–Al–Co, Cu–(Zr,Hf)–(Y,Gd)–Al and Gd–(Zr,Ti)–Al–Co alloy systems. The phase-separating MG systems can offer a unique opportunity for designing composites with hierarchical microstructure with different length scales and with enhanced plasticity, which was reported in Ni–Nb–Zr and Cu–Zr–Be ternary BMGs. U. Ramamurty (IISc, India) discussed the fracture and fatigue aspects in glasses with special emphasis on free-volume-shear banding-toughness connection, ductile–brittle transition and the origins of kinematic irreversibility causing fatigue. N. K. Mukhopadhyay (BHU, India) presented results on pop-ins effect from nanoindentation experiments of Cu-

based BMGs. He showed the similarity with nanodeformation of quasicrystals by way of shear-band formation and nanocrystallization.

E. Ma (USA) discussed the 3D packing of atoms in several models of MGs with different chemistry and atomic sizes. It was shown that by utilizing the concepts of efficient packing of space and topological instability, our understanding of GFA and BMG-forming compositions could be improved. The protocols developed from this approach were used to determine high GFA composition. D. B. Miracle (USA) advocated the efficient cluster packing (ECP) of atomic structural model for MGs for filling the space with unequal spheres. Structural arrangements using solute-centred clusters were able to describe the short and medium-range order and the topology for a broad range of MGs. In addition, ECP was used to predict density and atomic fraction that are in close agreement with experimental data. T. Egami (USA) pointed out the inadequacies of the 'free volume theory' of Cohen and Turnbull, though it explains the relaxation phenomenon and deformation. Among several other theories, it was shown that the one based on 'fluctuating topology of atomic connectivity' dealing with continuum mechanics at the atomistic level and statistical mechanical description of the local topological fluctuation, could successfully explain the glass transition temperature, viscosity, compositional limit for glass formation, mechanical deformation, atomic-level stresses and elastic moduli. Also, this theory provides the atomistic basis for successful phenomenological theories for the formation of MGs. Y. Hirotsu (Japan) reported on the HREM observations using the Cs-corrected TEM to visualize the locally ordered regions and nanobeam diffraction to study the local crystalline configuration. From these studies, structural fluctuation in glasses was found. It is interesting to note that in Fe–Nd–B MGs local bcc-Fe clusters and compound-like clusters were identified by these microscopic techniques. After annealing, local bcc-Fe clusters were clearly visible. Therefore, the high nu-

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cleation density of this glass in the primary nanocrystallization stage was better explained. S. Sastry (JNCASR, India) discussed some aspects of what makes a material a good glass former by way of weakening the three-body interactions, which leads to the destabilization of diamond crystals and emergence of the BCC crystal as stable form. The theoretical results obtained in a monoatomic glass former were compared with those of MG formers.

A. Takeuchi (Japan) proposed a prototype of composition criteria for BMG derived from general composition dependence of BMG formations. The prototype has a possibility to predict new BMG formations with compositions at around a couple of tens of atomic per cent on the basis of compositions analysed empirically and statistically. S. Ranganathan (IISc) outlined the synthesis routes for quasicrystalline materials and discussed the Mackay, Bergman, Kuo and Tsai approximants. Using the Mendeleev number and the Pettifor map, he demonstrated that most quasicrystals are pseudobinary. The link between the quasicrystals and BMGs was elaborated. J. W. Yeh (Taiwan) studied the GFA in equal-mole alloys, which are known as high-entropy alloys. The thin film developed from high-entropy alloys showed the existence of nanosize structure along with amorphous structures. Molecular dynamics simulations were used to examine the structural evolution and verify the trend in a series of high-entropy alloys. A. Inoue (Japan) reviewed developmental studies on the application of bulk glassy alloys. He discussed empirical rules for the formation of glassy alloys and drew attention to the achievement of maximum diameter over 20 mm in case of Cu-based alloys. The newly developed bulk glassy alloys were mentioned along with their possibility for potential applications. Y. Li (Singapore) proposed a scheme for deriving a practical strategy in locating the glass-forming ability, based on phase selection of the glass over all competing crystalline phases. It was suggested that the best glass-forming zone will be either symmetric or asymmetric about the eutectic composition and eventually a microstructure-based strategy was formulated to pinpoint the off-eutectic composition with optimum GFA. Several BMGs and their composites were determined by this approach. J. Saida (Japan) discussed the

approach to investigate GFA through local structure and quasicrystallization. Local structural changes during the transformation of Zr-(Cu or Ni)-(Al) MGs from the viewpoint of stability of supercooled liquid state as well as a quasicrystal formation were monitored. It was suggested that the stability of supercooled liquid state and BMG ability are strongly related with icosahedral local structure in the glassy state. C. Dong (China) advocated the cluster-line approach for determining the bulk glass-forming systems. This approach worked well in the case of quasicrystalline phase composition. Both binary and ternary clusters constructing the cluster lines satisfy the topological dense-packing requirement and the formation of all BMGs is closely related to these clusters. B. S. Murty (IIT Madras, India) discussed the preparation of BMGs by mechanical alloying. It was suggested that amorphization is controlled by total energy of milling and thus correlation between the energy required for amorphization and the enthalpy of mixing of BMGs could be established. It was observed that amorphization occurs when crystallite size and strain in the lattice reach a critical value. A parameter that combines the thermodynamic and topological approaches to identify the best glass-forming composition in multicomponent systems has been demonstrated. G. K. Dey (BARC, India) has studied in detail the interface between glassy and crystalline phases. The role of oxygen and quenched-in nuclei on nanocrystal formation behaviour and crystallization kinetics has been compared. J. Shen (China) advocated a new approach for finding out the BMG composition based on the concept of suppressing the crystallization event. Based on this approach, the base composition of a new BMG was found by mixing proportionally, the corresponding binary eutectic composition. The new GFA criterion, derived based on the classical theory of nucleation, growth and the kinetics of phase transformation was shown to explain many experimental results. R. K. Mandal (BHU) proposed a Venn diagram based on compositionally related parameters for classification of BMGs into two categories. It was shown that one class follows the Fermi surface-Brillouin zone interaction, whereas the other does not for stabilization.

Atakan Peker (USA) presented a brief history of the bulk solidifying amorphous

alloys. The commercial development of some BMGs by liquidmetal technologies was described. The leading family of these alloys, Zr-Ti-Ni-Cu-Be system with section thickness of 30 mm was prepared. It was mentioned that near net-shape component fabrication with reduced post-finishing processes is the added advantages for BMGs for many engineering applications. E. Fleury (Korea) presented recent results on the application of Fe-, Ni- and Ti-based BMGs for hydrogen generation, storage, purifier and bipolar plates in fuel cell. It was emphasized that the amorphous alloys could be considered as viable alternatives for these applications. U. Kamachi Mudali (IGCAR, India) discussed the mechanisms for corrosion of BMGs and pointed out that Zr-based BMGs have the potential for nitric acid application. It was shown how the pitting corrosion initiation and the local dissolution took place on the surfaces. Consequently, this altered the surface compared to the uniform surface of the non-corroded BMGs. J. H. Kim (Japan) presented various welding technologies of BMGs with crystalline metals (Zr, Ti, Ni, W, Al) by explosion, friction, pulse current and electron beam-welding processes. Evolution of microstructures and the consequent properties of the weld were discussed. D. Akhtar (DMRL, India) showed that partial nanocrystallization of some Fe(Co)-based glasses results in enhanced soft magnetic properties due to strong ferromagnetic coupling of nanocrystalline particles with amorphous matrix. Similarly, controlled devitrification of amorphous rare earth-transition metal alloys can lead to nanocomposites containing both soft and hard magnetic phases, and improved hard magnetic properties. A. Mitra (NML, India) discussed the development of Fe-based BMG as soft magnetic materials for large size components. It was shown that this material having low Curie temperature could not be used for high-temperature magnetic application. Attempts have been made to develop amorphous/nanocrystalline materials exhibiting high Curie temperature. It was pointed out that nanocrystallization was beneficial in many Fe-Co-based ferromagnetic MGs.

A special feature of the workshop was the hour-long interaction between the US delegates and the participants under the aegis of the Indo-US Science and Technology Forum. M. Atzmon, T. Egami, E. Ma, C. Schuh and A. Peker outlined the

research interests of their groups as well as those of their colleagues. There was a question-and-answer session. It is hoped that robust cooperation between US and Indian scientists will emerge from this event.

It is obvious that the discovery of MGs in 1960, quasicrystals in 1984 and BMGs in 1988 has undoubtedly attracted considerable research attention on these

complex metallic alloys because of fundamental interest and the possibility of technological applications. A consensus is slowly emerging as to what alloys can form glasses, the basic structural features, and the mechanics/mechanisms of deformation in them. It is also becoming clear that research will continue in the direction of BMG-based composites for

structural, magnetic and other applications.

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MEETING REPORT

Quality improvement in food processing*

The scenario of the food industry in our country has undergone a sea change during the last couple of decades. People have become enormously quality-conscious in matters related to food, rendering the industry fairly competitive. Indiscriminate use of harmful ingredients, preservatives, processing chemicals, etc. is seriously affecting the quality of food. On the other hand, horizons of food science and technology have expanded. A good number of food-safety regulations are prevalent in the country. These include the Prevention of Food Adulteration Act (Ministry of Health), the Agriculture Produce (Grading and Marketing) Act (Ministry of Rural Development)-AGMARK, laws being operated by Bureau of Indian Standards, a number of mandatory quality control orders under Essential Commodities Act such as FPO, MMPO, Meat Product Order and Vegetables Control Order. These multiple laws need to be harmonized.

It is in this context that a national conference was organized by the Indian Association for Productivity, Quality and Reliability (IAPQR), Kolkata. The conference provided a platform for focused discussions by acknowledged experts in the field from academia, industry, consumer fora and regulatory bodies, from different parts of the country.

S. P. Mukherjee (IAPQR) in his presidential address gave a brief introduction about IAPQR and also mentioned some of its activities. According to him, IAPQR established in 1972 with the primary objective of building-up the necessary human resource in quality personnel of the Indian industry, has since its inception been engaged in the pursuit, propagation and promotion of concepts, methods and practices to enhance productivity in manufacturing and service organizations through the practice of quality and reliability. Training is an area of strength of the Association, Mukherjee added. It offers through contact programmes and correspondence, an integrated two-year course on quality management, affiliated to the University of Burdwan. The Association also organises, from time to time, short-term programmes in quality-related areas and also carries out consultancy assignments on implementation of ISO 9000 Series of Standards (including Revision 2000) in several industries across the country.

Asim K. Duttaroy (University of Oslo, Norway) delivered the keynote address on 'The environmental health: Food and security'. He discussed in great detail the background of public and environmental health, definitions and importance of the food system and strategies to protect it. Core functions of public health, according to him, include assessing public health, promoting sound policies and assuring effectiveness. He defined environmental health as programmes designed to protect the public from hazards which exist or could exist in the physical environment. Environmental links to health concerns like drinking water, food, land, built environment, indoor air and emergencies were also elaborated by Dutta-

roy. Agro-terrorism (terrorism directed against agriculture, livestock, or other food supplies with biological, chemical, physical or radiological weapons), importance of preventing food-borne diseases, potential contaminants in food, strategies for prevention and risk reduction, and hazard analysis critical control points, were also covered in his lecture. Private and public cooperation is required to maintain and strengthen the food system, and core public health measures help ensure safer food, including assessing threats, developing common sense and practical policies, Duttaroy concluded.

In Technical Session I, J. Chakraborty (Central Food Laboratory, Kolkata) spoke on 'Modernization of Indian food safety and standards regulation'. The *Codex Alimentarius*, according to Chakraborty, has relevance to international food trade. With respect to the ever-increasing global market, in particular, the advantages of having universally uniform food standards for the protection of consumers are extremely important. It is not surprising therefore, that both the Agreement on the Application of Sanitary and Phytosanitary measures and Agreement on Technical Barriers to Trade encourage the international harmonization of food standards. As such, *Codex* standards have become the benchmark against which national food measures and regulations are evaluated within the legal parameters of the World Trade Organization (WTO) Agreements. The Prevention of Food Adulteration (PFA) Act, 1954 has laid the basis for a constructive and responsible consumer protection, including assistance to trade in India, according to Chakraborty. India is a signatory to WTO. Thus harmonization of PFA stan-

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