on fire or detonation-related aspects of hydrogen-air during possible accident scenarios of nuclear power plants. While several aspects of combustion have been or can be understood within the known knowledge base, deflagration–detonation transition in such instances needs further research.

Two presentations discussed laminar premixed flame speed determination and related aspects. C. Pratap (Indian Institute of Space Technology, Thiruvananthapuram) presented measurements on flame speed in spherically expanding flame technique and calculations using PREMIX code with GRIMech3.0 chemical kinetics. Sudarshan Kumar (IIT Bombay) presented a review of various techniques for measuring laminar burning velocities, bringing out inconsistencies in the results and ways of rationalizing the temperature dependence of the burning velocity.

Nagendra Babu (Vehicle Research and Development Establishment, Ahmednagar) presented the use of commercial diesel engines for UAV applications.

The major takeaways from the workshop were intensive interactions on both the fundamental and applied aspects of combustion science. A few collaborations and joint projects of relevance to solid propellant combustion, etc. may also emerge from this workshop.

1. Shivakumar, V., Ramakrishna, P. A. and Mukunda, H. S., *Curr. Sci.*, 2015, **108**(8), 1412–1413.
2. Mukunda, H. S., Bijukumar and Ramakrishna, P. A., *Curr. Sci.*, 2016, **111**(9), 1440–1442.

H. S. Mukunda*, 45th km, NH 209, Jakkasandra Post, Kanakapura Taluk, Ramnagar Dist. 562 112, India; **P. A. Ramakrishna,** Department of Aerospace Engineering, IIT Madras, Chennai 600 036, India; **Arvind Kumar,** HEMRL, Sutar Wadi, Pune 411 021, India.
*e-mail: hsm.cgpl@gmail.com

MEETING REPORT

High entropy materials*

High entropy materials (HEMs) as a research field in materials science and engineering has matured over the last few years. In 2004, Yeh *et al.*[1] and Cantor *et al.*[2] coined the term 'high entropy alloys' (HEAs) for the newly discovered multicomponent and multiprincipal (CoCrFeNiMn) metallic cocktails[3]; research activities were mainly centred on the metallic alloys. This has led to the discovery of many FCC and BCC HEAs[4], including refractory HEAs[5]. In 2012, a novel entropy stabilized multicomponent ceramic alloy was reported[6] and thus, the materials or phases predominantly stabilized by configurational entropy of mixing are now known to be HEMs. It has expanded the field, opening up new vistas of exciting research on these materials. This field has recently emerged as one of the most fascinating and challenging areas of materials research.

In order to take stock of the advancement, the second international workshop on HEMs was held. The first workshop was held in 2015 at IIT Madras[7]. The second workshop attracted scientists from academia, national laboratories as well as industries to understand the latest development in the area of HEMs. The workshop was attended by 150 participants, including several delegates from Austria, Australia, Germany, Taiwan and USA. There were 22 oral and 30 poster presentations. The first International Conference on High Entropy Materials (ICHEM) was held in Taiwan[8].

The workshop began with a brief address by B. S. Murty (IIT-Madras) and a welcome speech by M. Ghanashyam Krishna (School of Engineering Sciences and Technology, University of Hyderabad (UoH)). The technical session began with a plenary lecture by J. W. Yeh (National Tsing Hua University, Taiwan) on the issue of breakthrough applications of HEAs. He pointed out the possibilities of several potential applications, such as turbine blades, moulds/dies, and radiation damage-tolerant materials for atomic energy applications. The most important among them is the development of new bond coat for turbine blades in gas turbines, steam turbines, etc. He has extensively studied $Ni_{30}Co_{33.5}Cr_{21}Al_5Y_{0.5}$ HEA composition for such applications. In addition, HEAs could find applications in cutting tools, hard facing for wear-resistant parts; helium-cooled fast-breeder reactor, etc. Murty discussed challenges in HEA research, especially in the interpretation of experimental data on diffusion in these multicomponent alloys obtained by his research group using tracer diffusion at Germany. It is evident that the diffusion coefficient in these alloys must be scaled with melting temperature of the alloys for any relative comparison. D. Miracle (USA) described the strategies to accelerate development of novel HEMs. According to him, combinatorial approach can dramatically accelerate the development of HEMs by rapid scanning of compositional landscape. R. Banerjee (USA) discussed the aspect of thermodynamic equilibrium in HEMs. Obtaining a single-phase HEA in a large temperature range is constrained by the precipitation of second-phase during cooling to lower temperature. Using $Al_{0.3}$CoCrFeNi HEA-forming system, he demonstrated the formation of second-phase precipitates by heat treatment at different temperatures, which is controlled by competition between thermodynamic driving force, activation barrier of nucleation and kinetics of the process. K. Kulkarni (IIT-Kanpur) described the role of cross effects in multicomponent diffusion prevalent in HEMs. These effects are due to relative thermodynamic interactions and differences in individual interdiffusion coefficient. In case of Co–Cr–Fe–Ni equiatomic alloy, he advocated methods of calculation of the

*A report on the 2nd International Workshop on 'High Entropy Materials' (IWHEM) jointly organized by the University of Hyderabad (UoH) and Indian Institute of Technology (IIT), Hyderabad at the UoH during 11–12 March 2017.

cross-diffusivity terms relevant for multicomponent diffusion. G. Phanikumar (IIT-Madras) presented research on the effect of undercooling on phase selection and solidification pathways of CoCuFeNi$X_{0.5}$ alloys. Increasing undercooling significantly alters the free energy available for nucleation and growth of different phases during solidification. Using undercooling as an important process parameter, phases and microstructure in the aforementioned alloy could be changed to dendritic phase with eutectic or even single-phase equiaxed microstructure. J. Bhatt (NIT-Nagpur) described thermodynamic modelling for optimization of non-equiatomic bulk metallic glass compositions. The major challenge in designing metallic glasses lies in obtaining the binary chemical interactions. Thus a comprehensive topological along with thermodynamic modelling is required to select HE compositions, suitable for metallic glasses. R. Misra (USA) made a presentation on the estimation of strength–ductility combination in various FCC HEAs. He categorically mentioned that strength–ductility combination of several FCC HEAs estimated by compression is not suitable, as ductility during compression test is rather shielded from failure processes and thus, more tensile test data are required for realistic evaluation of strength–ductility behaviour of these novel alloys. P. P. Bhattacharjee (IIT-Hyderabad) described recent research on thermomechanical processing of eutectic $AlCoCrFeNi_{2.1}$ alloy. Using both normal as well as cryorolling techniques followed by annealing treatments, his group showed intriguing deformation and recrystallization behaviour of these alloys revealing attractive strength–ductility combinations. R. S. Kottada (IIT-Madras) presented work on creep behaviour of equiatomic quarternary nanocrystalline CoCrFeNi HEA, synthesized via mechanical alloying followed by spark plasma sintering. Constant stress creep experiments carried out in the 600–900°C temperature range and at stress levels of 50–300 MPa indicate that dislocation-mediated creep is the rate-controlling mechanism in this multicomponent alloy. The alloy is found to be thermally stable against grain growth even up to $0.5T_m$. K. Biswas (IIT-Kanpur) discussed the stability issues of two HEAs. The thermal stability of equiatomic CoCuFeMnNi has been studied by *in situ* X-ray diffraction, which indicates that the FCC phase is stable only at higher temperature (>850–1450°C), whereas at lower temperatures, it transforms to FeCo-rich BCC phase. For equiatomic CoCuFeNiTi, processed using powder metallurgy powder metallurgical route single FCC phase in mechanically alloyed powder undergoes spinodal decomposition, leading to a nanoscale phase separation with the formation of (Cu,Ni)-rich and (Fe,Co)-rich solid solution.

Y. Ivanisenko (Germany) discussed recent work on severe plastic deformation of AlCrFeCoNiCu and CoCrFeNiMn alloys using high-pressure torsion (HPT). HPT is a technique utilized by materials scientists to prepare ultrafine and nanocrystalline alloys. She has demonstrated the formation of nanotwins in these FCC HEAs and their role in the deformation mechanisms. A. S. Gandhi (IIT-Bombay) presented interesting work on multicomponent equimolar oxide ceramics, popularly known as entropy-stabilized oxides. Using co-precipitation and spray or flame spray pyrolysis techniques, (Co,Cu,Mg,Ni,Zn)O oxide having NaCl-type structure and (Ce,Gd,La, Nd,Pr, Sm,Y)O with FCC structure have been synthesized. Calculation of configurational entropy in oxides is known to be different because oxygen sublattice does not contribute and thus, configurational entropy is mainly decided by cation sublattice(s). K. G. Pradeep (Germany) discussed novel combinatorial design approach for developing HEMs. Using a rapid alloy prototyping approach, dual-phase alloys in $Fe_{80-x}Mn_xCo_{10}Cr_{10}$ system have been synthesized. This approach allows us to rapidly scan various compositions for the possible formation of HE phases, and to design non-equiatomic alloy with dual-phase microstructure and with optimum mechanical properties. S. R. Bakshi (IIT-Madras) described his work on the effect of alloying addition on phase formation and mechanical properties of Ti–Al–Ni–Co–Cr–Fe multicomponent alloy, synthesized via mechanical alloying and spark plasma sintering. These alloys are tested for high-temperature oxidation and wear. C.-W. Tsai (Taiwan) discussed the mechanical properties of single-phase HEAs, especially $Al_{0.5}CoCrCuFe$ and $Al_xCoCrCu_yFeNi$ (x, $y = 0.2$ or 0.3) alloys. By reducing Cu content in the former, his group could prepare a single-phase FCC alloy. Detailed study on the mechanical properties establishes twinning to be the dominant mode of deformation. S. Abhaya (IGCAR, Kalpakkam) made a presentation on the use of positron annihilation spectroscopy to understand defect microstructure in CoCrFeNi HEA. This technique allows non-destructive characterization of defects to study vacancies ranging from mono vacancy or even clusters. The application of HEMs in atomic energy reactors requires them to have enhanced radiation resistance and thus, these studies will shed new light on potential application of HEMs. K. V. Rajulapati (UoH) presented detailed work on understanding the mechanical behaviour of ultrafine-grained equiatomic AlCoCrCuFeNi HEA, synthesized by mechanical alloying and sintering. It has been possible to deconvolute different strengthening mechanisms, including frictional stress, Taylor hardening, solid solution hardening, Hall–Petch hardening, twin-boundary mechanism in HEAs from data obtained using Vickers as well as nanoindentation tests. K. R. Ravi (PSG Institute of Advanced Studies, Coimbatore) made a detailed presentation on HEA design, highlighting the advantages of using CALPHAD approach with the existing thermodynamical databases. Using three different databases, SSOL4, TCFE8 and TCNI7, he illustrated various HEA forming systems, highlighting the caveat of using these databases for alloy design. There were three interesting presentations on applications of HEMs using a variety of techniques. C. C. Berndt (Australia) discussed the role of thermal spray deposition to obtain coatings of HEMs. He stressed upon the fact that the properties of these coatings will strongly depend on controlling non-equilibrium nature of the process. Using spherical powder particles of equiatomic CoCrFeMnNi HEA as feedstock, he demonstrated the advantage of using thermal spray to prepare efficient coatings on different substrates. D. Fabijanic (Australia) showed several examples of direct laser manufacturing of HEAs. It is to be noted that this is an additive manufacturing technique to obtain near net shape of bulk components and overlay coatings. He has shown the successful fabrication of both chemically homogeneous $Al_xCoCrFeNi$ ($x = 0.3$, 0.6, 0.9) bulk and coatings on 253MA stainless steel as well as Inconel 600 superalloy using blended elemental powder. Depending on

Al concentration, crystallographic nature of the product can be tuned from FCC to FCC/BCC and to BCC phases. Detailed tensile testing of the deposited coatings reveals strong texture developed during solidification. He pointed out that the area of additive manufacturing of multicomponent alloys is still in the nascent stage and there exists opportunity for suitable applications. S. V. S. Narayan Murty (VSSC, Thiruvananthapuram) highlighted the problems of HEMs with regard to their commercial applications. He further stressed upon the formulation of proper direction of work for future prospects. Some of these problems are related to cost, ease of manufacturing, recyclability, etc.

Overall, the workshop led to many stimulating discussions among the delegates on various fundamental aspects of advanced research on HEMs as well as the existing challenges. Many distinguished materials scientists participated in the brain-storming discussions, on the use of thermodynamics database, precise chemical composition at different stages of processing, defects characterization during deformation and diffusion data analysis in these multicomponent systems. It emerged that high-purity elements and precise processing lead to cost escalation of developing new alloys centred on high-entropy concepts. It was also suggested that the starting materials may be HEAs, but subsequently it may decompose to low-entropy phases. It was realized that first-principles calculation along with other computational tools should be used to understand the phase stability and phase selection. However, research in this area is exciting due to the possibility of developing and substituting strategic components using HEMs, which can eventually provide better services. It was agreed that collaboration among various groups would be important to resolve several fundamental issues. It may noted that a website on HEA (https://mme.iitm.ac.in/hea/) is maintained at IIT-Madras to share information of latest publications and the groups working in India. The next workshop will be held in 2019 at IIT-Kanpur.

1. Yeh, J. W. *et al.*, *Adv. Eng. Mater.*, 2004, **6**, 299–303.
2. Cantor, B. *et al.*, *Mater. Sci. Eng. A*, 2004, **375–377**, 213–218.
3. Ranganathan, S., *Curr. Sci.*, 2003, **85**, 1404–1406.
4. Tazuddin, N. P. Gurao and Biswas, K., *J. Alloys Compds.*, 2017, **697**, 434–442.
5. Senkov, O. N., Isheim, D., Seidman, D. N. and Pilchak, A. L., *Entropy*, 2016, **18**(3), 102–106.
6. Rost, C. M. *et al.*, *Nature Commun.*, 2015, **6**, 1–8.
7. Mukhopadhyay, N. K., *Curr. Sci.*, 2015, **109**(4), 665–667.
8. Biswas, K., *Curr. Sci.*, 2017, **113**(9), 1648–1649.

Krishanu Biswas*, Department of Materials Science and Engineering, Indian Institute of Technology-Kanpur, Kanpur 208 016, India; **N. K. Mukhopadhay,** Department of Metallurgy, Indian Institute of Technology, Banaras Hindu University, Varanasi 228 001, India.
*e-mail: kbiswas@iitk.ac.in

MEETING REPORT

Breeding for crop improvement*

A one-day dialogue on breeding strategies for crop improvement was held on 10 July 2017.

V. Praveen Rao (Professor Jayashankar Telangana State Agricultural University (PJTSAU), Hyderabad) opened the dialogue stating that the purpose was to integrate fundamental knowledge on breeding for crop improvement with what new technologies offer to raise crop production. The World War II imposed a severe shortage of food. Technology that was generated then, quickly came to the rescue of humanity in mid-1950s to mid-1960s. Two outstanding scientific developments are dwarf plant types in wheat and rice to produce more harvestable grain yields which helped India reach self-sufficiency in food and other necessities for a comfortable life. Global population and food production have increased by several folds. The Indian population has also grown to 1.3 billion. We need 370–425 million tonnes by 2050 to feed our population. Rao further stated that this programme was aimed to address the major challenges to agriculture in the world today: (i) How to remain self-sufficient in food and other needs? (ii) How to reach the targeted crop production with less resources and in an economically acceptable and ecologically sustainable manner? (iii) How to face climate change, especially the frequent occurrences of droughts, floods, unpredictable weather vagaries near harvest and rising temperatures? T. Mohapatra (ICAR, New Delhi) chaired the dialogue and suggested the need for innovative technologies in agriculture to double farmers' income. Science has advanced from Mendelian genetics to molecular breeding, transgenic breeding and genomics-associated breeding. He called for intensified trait discovery; breeding strategies to manipulate postharvest traits in crops and find ways to reduce the use of resources like fertilizers and water to get optimized yield. Zikang Li (Institute of Crop Sciences, China) delivered a keynote address on the 3K Rice Genome Project and its implication to future rice improvement. His group has identified 42 million single nucleotide polymorphs (SNPs) in Rice Pan Genome and >12,000 novel genes that are absent in single reference genome. They have also detected structural variation, and transposition and deletions as predominant structural changes. The haplotype diversity will be used to understand gene function and large-scale gene/quantitative trait loci (QTL) discovery and allele mining by GWAS (genome wide association studies). E. A. Siddiq (PJTSAU) emphasized on the

*A report on the one-day dialogue on 'Modern Breeding Strategies for Crop Improvement' held on 10 July 2017 at Professor Jayashankar Telangana State Agricultural University, Hyderabad.