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Symposium Review: Solidification Processing of Metal Matrix Composites - Rohatgi Honorary Symposium

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Metal Matrix Composites (MMCs) are used in a large number of high performance applications in the present times. The usage of MMCs was over 3.5 million kg in the year 2004 and is increasing rapidly at an annual growth rate of over 6%. Most of their current applications are in ground transportation, aviation, electronics and sports industries.

The initial discovery of the synthesis of cast Aluminum matrix composites including Al-Graphite, Al-SiC, and Al-Al_2O_3 particulate cast MMCs was made by Dr. Pradeep Rohatgi in 1965 at the Merica Laboratory of the International Nickel Company. As a result of this discovery, the fundamental understanding of solidification processing of MMCs, and the technology related to manufacture and use of these composites has come a long way. A symposium, *Solidification Processing of Metal Matrix Composites*, was organized as a part of the TMS Annual Meeting 2006 to commemorate the 40th anniversary of the initial discovery made by Dr. Rohatgi and his continued efforts over the last four decades. Hence, the symposium was designated as the "Rohatgi Honorary Symposium." The symposium was organized by Dr. Nikhil Gupta of Polytechnic University, Brooklyn, and Dr. Warren Hunt of Aluminum Consultants Group Inc. It was sponsored by the TMS Materials Division, TMS/ASM, Composite Materials, and TMS Solidification Committee.

The goal of the symposium was to look at the developmental path of MMCs, and determine the future directions for research and applications. The symposium was divided into six sessions, which cover five broad fields of "*Overview of Developments in MMCs*", "*Processing and Microstructure*", "*Properties*", "*Modeling and Nanocomposites*" and "*Advanced Applications*." In total, 50 oral presentations were planned in the symposium and a proceedings containing 32 of these papers was published by TMS. These papers range from review papers detailing the historical perspective and significant milestones, to the frontiers of research in the present times. The final session had a group discussion on the "*Future Directions in Metal Matrix Composites*" moderated by David J. Weiss of ECK Industries Inc.

The Symposium started with a brief introduction to the life and work of Prof. Rohatgi presented by many of his peers, coworkers and MMC researchers from the USA, India, and Poland. Warren Hunt, Merton Flemings, Ray Decker, Jerzey Sobczk, and K. G. Satyanarayana recalled their association with Prof. Rohatgi at different times and highlighted his contributions in the field of MMCs. Ray Dekker, who was present with Dr. Rohatgi when he synthesized the first MMC in 1965, recollected the event and provided a first hand description of the event to the symposium audience. Flemings commented on the historical importance of this discovery in advancing the field of solidification processing of MMCs and recollected his continued interaction with Rohagti, including his visited Dr. Rohatgi's laboratories in India.

Prof. Rohatgi opened the technical sessions by presenting a timeline of historical evolution of cast MMCs, current challenges and outlined the future directions in research and industrial applications. He talked about his early excitements, during processing of Al–graphite and Al-SiC composites and later work on theoretical and experimental studies on microstructure formation, properties and applications of Al and Mg based MMCs, lead free Cu-Graphite MMCs and syntactic foams. He also touched upon the future research needs in the cast MMC technology and possibilities of extending this technology to metal matrix nanocomposites and functionally gradient materials to meet the rising performance demands. David Weiss presented the current and potential applications of Al-based MMCs in electronic packaging, automotive and aerospace sectors. He outlined several research challenges in the field including design and control of solidification microstructures, including distribution of reinforcements and nature of interface. He reviewed the research done in the field in different countries, mainly in the US and India, and chronicled the uses of these composites in last forty years.

Nikhil Gupta discussed hollow particle filled composites called syntactic foams. These advanced lightweight composites have high energy absorption capabilities. Low cost syntactic foams can be synthesized by using fly ash cenospheres, which is a waste materials generated by thermal power plants. He presented a technique of controlling the mechanical properties of these materials through the wall thickness of hollow particles, which is more effective than other means. Dr. Satyanarayana, who worked with Prof. Rohatgi in Regional Research Laboratory – Trivandrum (RRL-T), India reviewed the contributions from India. He stressed on the work done in using locally available materials as reinforcements for the synthesis of MMCs. He concluded his presentation with the opportunities for using cast MMCs in developing countries such as India. In his other paper he outlined theoretical and experimental studies related to mixing, wettability and surface treatments carried out in India. He discussed present patents, market, quality and cost aspects of cast Al-MMCs, and concluded with an outline of the necessary steps to achieve faster growth of cast MMC applications.

In view of challenges in obtaining uniform distribution of reinforcements, Dr. Reddy of University of Alabama presented *in situ* processing techniques for synthesizing Al and Mg matrix composites containing SiC and AlN through bubbling of reactive gases such as methane and

nitrogen. He discussed the effect of processing parameters for the formation of ceramic reinforcements, kinetics for the obtaining these composites with incorporation up to 30 wt. % of SiC. Anil Gupta of National Physics Laboratory, India presented the status of the work carried out in his Laboratory on Al-SiC_p, carbon/carbon and nano-composites. He stressed on the primary and secondary processing of Al and Mg based composites, structure-properties relationship and the prototypes made and tested.

The next two sessions were focused on the structure and properties of cast MMCs dealing with both theoretical and experimental results. In his paper, Prof. Stefanescu, discussed several theoretical models on particle pushing during solidification synthesis of MMCs. Experimental results on the interfacial reactions in the synthesis of Al-12Si-Cu-Mg-Ni-short fibers of Saffil and Kawool were then presented by Karl U Kainer, bringing out dependence of these reactions on fiber composition and their effects on the mechanical properties, particularly on aging. Natalia Sobczak, Jerzy Sobczak and their group from Poland presented results of experiments on reaction between oxides [B_6O, CaO, MgO, SiO_2, ZrO_2, ZnO and TiO_2] and molten Al to demonstrate the possibility of *in situ* synthesis of MMCs. They also discussed their work on powder metallurgy and stir casting synthesis of light weight Al-fly ash composites for automotive applications, such as pistons and brake rotors.

Four papers discussed Mg-based composites. Adam Loukus highlighted the effects of solidification on morphology and mechanical properties of Mg matrix composites, while the results from University of Wisconsin-Milwaukee highlighted successful application of stir casting technique to Mg-fly ash system. Another paper discussed the use of ultrasonic mixing and the addition of Mg during the fabrication of infiltrated Al-C_f composite, which improved the quality of the MMC. The possibility of electrical cables made of such composites replacing conventional steel cables was highlighted. Interesting and promising results obtained in an Mg matrix composite containing metallic particles such as Cu, Ni, Ti and Mo processed by disintegrated melt deposition coupled with hot extrusion were presented from the National University of Singapore. The addition of rare earth such as Ce during the partial remelting of Mg-TiC composite particles revealed not only the entrapment of these Ce particles within the α-Mg grains, but also the presence of most of the TiC particles in the liquid phases distributed at the grain boundaries.

An economic and novel technique developed by ALCAN for liquid mixing for the shape casting of Al-Si-B_4 composites was presented by Dr. Chen. He revealed that particles affected the solidification process, whereby the distribution was not uniform, and the reaction layer played an important role in limiting the interfacial reaction in the composite. Rohatgi presented the work of his group on extracting heat by cooling the ends of reinforcing carbon fibers during processing. The fibers acted as source of heat extraction and yield novel interfaces and uniform matrix microstructure.

Presentation of successful infiltration of low mullite-silica spherical foams by liquid Al and tensile properties of the resulting composites were presented by Dunand of Northwestern University. Papers on synthesis and characterization of Zn-Al reinforced with SiC_p were other highlights of these sessions.

Prasad reviewed the friction and wear mechanisms in Al alloy matrix composites. He discussed how the hard or soft dispersoids could influence wear mechanisms. Weiss stressed the concern of automotive industry over the high cost of Al-MMCs. He discussed the importance of selective reinforcement to reduce the manufacturing cost. The effect of particle size and additions of Si and Mg in Al-SiC, on the synthesis parameters, wear, and mechanical properties of MMCs were discussed in other papers from Alicante University and Istanbul University. Laser deposition as one of the *in situ* synthesis methods was highlighted in a joint paper from Sandia National Laboratory and University of California, Davis.

In the session on Modeling and Nano composites K. K. Chawla pointed out that the analytical tools are not good at predicting the properties of particulate MMCs because they do not account for the microstructural features. He presented the microstructure based finite element modeling (FEM) techniques developed by his group to analyze particle reinforced MMCs. He showed the possibility of predicting elastic, plastic and thermal behavior of MMCs, through examples of Al-SiC and Wc-Co composite systems. Continuing with the modeling studies, Dr. B. Majumdar discussed the damage mechanisms and prediction of ductility in two cast Al-alloy systems. He showed that shape of brittle Si particles in both the alloys have complex 3-D morphology, which are not generally found in such alloy systems. He also presented a comparison of some of the experimental data obtained through mechanical tests and morphological studies including neutron and Raman spectra with the predicted ductility values for these alloy systems.

Garvin presented multi-scale models on particle-solidification front interaction including a new method for predicting the critical velocity for particle pushing. Yang presented a sharp interface level-set simulation to understand the dendrite-particle interactions using local mesh refinement technique. In this study they included the thermal conductivity parameters of both the particle and the melt, and interactions of multiple dendrites and multiple particles, making it possible to predict the resulting microstructure.

The invited talk on Nanocomposites by Meng presented the results of their recent work two-phase nano composite thin films of hydrogenated Carbon and Si_3N_4, both being amorphous, and synthesized by plasma assisted vapor phase deposition. An illustration of applications of the nanostructured thin film to micro-scale molding replication of metal based high aspect ratio materials was the highlight.

Miracle of US Air Force reviewed the current status in applications of MMCs in ground transportation, thermal management, aerospace and industrial and recreational fields. Some of the examples given included Ti-TiB intake and exhaust tubes in Toyata Altozza, Euro-copter blades and nozzles, Al-MMC transmission lines, and Ferro-TiC high wear parts. According to Miracle, the largest market volume, about 69%, is for Al based MMCs followed by 25% for refractory MMCs; liquid metallurgy processing is about two thirds of the market by volume and ¼ by the value. Herling of Pacific Northwest National laboratories presented the synthesis of low cost MMCs for ground based vehicles and discussed the cost –

performance balance for these MMCs. He pointed out that affordability is the main barrier for the use of MMCs along with a lack of design knowledge and engineering guidance. Jason Lo highlighted the development and use of a novel hybrid Al-SiC composite for brake applications. He discussed the A359-20SiC_p composite break rotor weighs only 3.3 kg resulting in about 60% saving in weight over the conventional product, resulting in 0.25 miles/gallon fuel saving.

The paper by Grant Chen discussed the use of B_4C containing composites in different Al matrices (AA6351, 6063, AA1100 and Al-Si) processed by casting, shaping by extrusion or rolling as neutron absorber in the nuclear industry. He pointed out that these composites are important since they serve nuclear criticality safety in dry storage and transportation of spent nuclear fuel, structural support of fuel assemblies and removal of heat during storage. The addition of Ti to the melt improves wettability of the dispersoids and also helps in getting their uniform distribution. He showed that AA6351-B_4C composites possess excellent extrusion performance and are heat treatable to develop good strength properties, 6063-B_4C possesses enhanced thermal conductivity, AA1100-B_4C composites provide highest B_4C loading and neutron absorption and good thermal conductivity, and Al-Si-B_4C composites showed excellent castability.

A group discussion moderated by Dr. Weiss was organized in the last session. The focus of the discussion was to identify issues that are limiting the widespread bulk applications of MMCs and to find future directions in research and applications. Among various views that emerged in the discussion, Indian participants expressed concerns about limited availability of cost effective preforms. The underlined the use of local materials for reinforcements. Canadian and the US participants expressed concerns about the machining and labor cost. Overall, a consensus emerged that the largest applications of MMCs can be found in transportation sector. Growing prices of energy may also lead to enhanced applications of MMCs in reducing the weight of vehicles and leading to better fuel efficiency. Useful suggestions from the panel included: understanding and using lower cost reinforcements, developing low cost machining, improved mixing technology, development of manufacturing infrastructure and a search for higher value-added applications. The symposium brought together researchers, users and producers of MMCs and thus enabled a lively discussion on future directions in the field of cast MMCs.

A photograph showing the first synthesis of cast metal matrix composites by Dr. Pradeep Rohatgi at Merica Laboratory at International Nickel in 1965. From left: Frank Badia, Pradeep Rohatgi and Charlie Kryda.