Merton C. Flemings Technical Program

Merton C. Flemings Symposium - 2000: Dendritic Solidification Dynamics

Wednesday AM Room: Wong Auditorium
June 28, 2000 Location: Tang Center, East Campus, MIT

Session Chairs: Reza Abbaschian, University of Florida, Matls. Sci. and Eng. Depts., Gainesville, FL 32611-6400 USA; Theodoulos Kattamis, University of Connecticut, Dept. of Matls. Sci. and Eng., Storrs, CT USA; Thomas Eagar, MIT, Dept. of Matls. Sci. and Eng., Cambridge, MA USA

8:15 AM Opening Comments
Reza Abbaschian, Thomas Eagar, Theo Kattamis

8:20 AM Keynote
Dendritic Growth: *Wilfried Kurz*[1]; Rohit Trivedi[2]; [1]Swiss Federal Institute of Technology, Dept. of Matls., Lausanne CH-1015 Switzerland; [2]Iowa State University, Dept. of Matls. Sci. and Eng., Ames Lab. US-DOE, Ames, IA 50011 USA

During most of his life Mert Flemings and his co-authors have made many original and significant contributions to areas related to dendrites, such as; coarsening of secondary dendrite arms, microsegregation, porosity, macrosegregation, semi-solid processing, dendrite growth in composites, directional casting and dendritic growth in highly undercooled melts. All these topics will be presented during the symposium. This contribution will concentrate on the very dendrite tip, the tip which more or less strongly influences most microstructural features of the solidified material. Both cases, undercooled and constrained dendrite growth will be treated. The now 15 years old Ivantsov-Marginal Stability (IMS) theory will be discussed and applied to large deviations from equilibrium, to multicomponent alloy systems and to solid state transformations. These extensions make this theory a generally useful tool which can be easily implemented in complex numerical codes for processing-microstructure modeling. Further the dendrite tip temperature (i.e. the interface response for varying interface velocities, temperature gradients, and compositions) will be used to produce microstructure and phase selection maps. Examples of application of such maps for solving some important solidification problems, such as hot cracking of stainless steels or microstructure control for epitaxial single crystal laser deposition on SX turbine blades, will be presented.

8:55 AM Keynote
Introduction to Phase Field Modeling of Alloy Solidification: *William Boettinger*[1]; [1]National Institute for Standards and Technology, 100 Bureau Dr., Stop 8555, Gaithersburg, MD 20899-8555 USA

Over the past few years a new modeling technique has been applied to solidification problems. The method has been used for a variety of problems including dendritic growth in pure materials and alloys, eutectic and peritectic growth, solute trapping at high velocity, effects of fluid flow on dendritic growth and coarsening of liquid-solid mixtures. From a mathematical perspective, the traditional method of treating solidification interface motion problems involves tracking the position of the interface and applying boundary conditions there. This difficult problem is avoided by defining a "phase-field" variable where the interfacial region between liquid and solid involve a smooth, but highly localized variation of this variable. A corresponding governing equation describes the state (solid or liquid) in the material as a function of position and time. Finite difference techniques on a uniform mesh can be used to predict the evolution of complex growth shapes. However, time constraints on the computations currently require compromises with regard to matching realistic solidification conditions. Despite the limitations, predictions are made for alloy dendritic growth that include the following effects: prediction of operating tip radius without extra conditions, microsegregation patterns including back diffusion,side-arm bridging and dendrite fragmentation.

9:20 AM
Phase-Field Modeling of Dendritic Evolution in Undercooled Melts: Youngyih Lee[1]; Alain Karma[1]; Mathis Plapp[1]; [1]Northeastern University, Phys. Dept., 360 Huntington Ave., Boston, MA 02115 USA

Dendritic growth in a pure undercooled melt is investigated in the two opposite limits of high and low undercooling using a quantitatively accurate phase-field approach. At high undercooling, we find that steady-state growth of the tip is destroyed by thermal fluctuations above a critical undercooling. This undercooling is comparable to the one corresponding to a universally observed break in the velocity-undercooling curve. These findings are related to recent experimental observations of the macroscopic envelope of the solidification front by Flemings and Matson using thermal surface profiles imaged during recalescence in electromagnetically levitated samples of pure Ni undercooled by different amounts. At low undercooling, we find a universal tip morphology that is independent of anisotropy strength. The amplitude of the non-axisymmetric deviation of this morphology from a paraboloid is about twice smaller than predicted by solvability theory and in good agreement with existing microgravity shape measurements in succinonitrile.

9:30 AM Keynote
Coarsening of Solid Liquid Mixtures: Morphology and Kinetics: *Peter Voorhees*[1]; Theo Z. Kattamis[2]; [1]Northwestern University, Matls. Sci. and Eng. Dept., 2225 N. Campus Dr., Evanston, IL 60208-3108 USA; [2]University of Connecticut, 97 N. Eagleville Rd., Storrs, CT 06269-3136 USA

Pioneering work on metal alloy dendrite coarsening was initiated at M.I.T in the mid sixties, aiming at fundamentally interpreting the observed dependence of dendrite arm spacing on local solidification time in a variety of alloys, and the formation of microstructure during solidification of bulk undercooled melts. Modeling of coarsening was tested by isothermal holding experiments in the solid-liquid region and continuous solidification experiments, for both dendritic and nondendritic binary alloys. It was found that remelting, dendrite fragmentation and accelerated coarsening during shearing of semi-solid mixtures controlled the microstructure in Rheocasting, a process developed and investigated by the Flemings group. Work of this group and other investigators will first be reviewed. Two topics in the area of coarsening of solid-liquid mixtures investigated at Northwestern will subsequently be discussed: the three-dimensional morphology of solid-liquid mixtures and the dynamics of coarsening in solid-liquid systems where the solid particles are connected by grain boundaries. The three-dimensional morphology of solid liquid mixtures has been determined, after quenching, by using multiple serial sections. A machine has been developed that allows more than 20 serial sections per hour to be made and recorded automatically with great accuracy. Using these serial sections, it is then possible to reconstruct the full three-dimensional microstructure with a computer. A major difference between solid-liquid mixtures and many solid-solid mixtures is that grain boundaries can form when two crystals of different orientation contact one another. In an effort to determine the effects of these grain boundaries on the coarsening process in solid-liquid systems, a phase-field model has been developed that allows for the presence of grain boundaries. Using this model in two-dimensions it is possible to determine, for example, the coarsening rate of a solid-liquid system as a function of the dihedral angle that is formed at the trijunction between the grain boundary and the two solid-liquid interfaces. Results of these calculations and examples of three-dimensional reconstructions of solid-liquid mixtures will be presented.

10:05 AM Break

10:20 AM

In-Situ X-Ray Imaging of Alloy Solidification: *Ragnvald Mathiesen*[1]; Frode Mo[1]; Lars Arnberg[1]; [1]Norwegian University of Science and Technology, Dept. of Matls. Tech. and Electrochem., Alfred Getz Vei 2B, Trondheim 7491 Norway

Solidification of alloys has been imaged by means of synchrotron X-radiation and a fast read-out, low noise detector at the European Synchrotron Radiation Facility (ESRF). A thin layer of melt is contained in a glass cell in a Bridgman apparatus, which allows solidification over a wide range of growth rates and thermal gradients. The detector records a 1x1mm image of the X-ray beam transmitted through the mushy zone with spatial and temporal resolutions down to 0.7mm and 0.7s, respectively. The collected images display features from both phase and amplitude contrast. Columnar dendritic solidification, has been studied in Sn-10wt%Pb alloys at moderate temperature gradients. Microsegregation and liquid boundary layers can clearly be seen. Macrosegregation is also frequently observed in this alloy. Cellular solidification at higher temperature gradients has also been studied. Crystal detachment and formation of new grains has been observed in this growth mode. Equiaxed dendritic solidification with continuous nucleation ahead of the solidification front has been observed in a Pb-48wt%Sn alloy over a variety of growth conditions. The collected images, which display quantitative information with features from both phase and amplitude contrast, combined with the attainable spatial and temporal resolution, provide the potential to uncover dynamic processes in non-equilibrium solidification. The results are expected to be useful for developing and evaluating theoretical models for dendritic growth and for a variety of other applications.

10:30 AM Keynote

Microsegregation: *Takateru Umeda*[1]; [1]University of Tokyo, Grad. Sch. of Eng., 7-3-1 Hongo, Bunkyo, Tokyo 113-8656 Japan

Microsegregation is inevitably accompanied with a solidification evolution. Microsegregation is a trace of solidification progress itself, therefore a prediction of microsegregation leads to know how to solidify quantitatively. Many attempts have been made, and will appear, to treat microsegregation from a matter of vital importance. The Brody-Flemings model blazed a trail, a landmark, in the field. In this report, a significant contribution of the Brody-Flemings model to developing theories of microsegregation phenomena and its present meaning are at first reviewed. In the second, many important theories followed with BF are referenced to focus their new findings in comparison with BF and also experimental results, in which composition distribution measurement methods, partition coefficients measurement and liquidus slopes measurement are included. In the third recent developments, especially application to multicomponent systems are discussed.

11:05 AM

Origins of Non-Equilibrium Segregation Theory: *Martin E. Glicksman*[1]; R. N. Hills[2]; [1]Rensselaer Polytechnic Institute, Matls. Sci. and Eng. Depts., Troy, NY12180-3590 USA; [2]Heriott-Watt University, Math. Dept., Edinburgh EH 14 4AS UK

The solute redistribution law that predicts non-equilibrium constitution in cored binary alloys is usually attributed to Eric Scheil. Much earlier studies on this subject published by G.H. Gulliver are occasionally cited, but are thought as being either approximate or incomplete. We show that Gulliver fully recognized and propounded the correct limit laws for non-equilibrium segregation in solidifying binary alloys no later than 1913—almost 30 years prior to the publication of Scheil□s paper. For reasons that remain obscure, however, Gulliver chose not to provide, or perhaps burden, the reader of his paper with the mathematical connection of his unusual derivation to the now well-known segregation power-law for binary solidification. By contrast, Scheil□s familiar integral form for this segregation law was derived from a straightforward mass balance, which today provides the standard mathematical setting to derive this important equation. The authors conclude that attribution and credit for this significant accomplishment in solidification theory should properly be shared by both researchers and called the Gulliver-Scheil equation.

11:15 AM

Freeze Preservation of Living Systems: *William E. Brower*[1]; [1]Marquette University, Dept. of Mech. and Indus. Eng., 1515 W. Wisconsin Ave., Milwaukee, WI 53233 USA

The principles of solidification which I learned in Professor Flemings□ group appear to apply directly to the field of cryobiology, the banking of living systems for transplantation. The formation of ice dendrites causes severe microsegregation of salt, since the partition coefficient for salt in water is essentially zero. Living cells are pushed ahead of the ice front (just as nonmetallic inclusions are in metals) and perceive the salt microsegregated extracellular (EC) liquid as hypertonic. To alleviate the osmotic pressure across the cell membrane, intracellular (IC) water perfuses across the membrane to dilute the EC liquid. Eventually, this leaves the IC liquid at a fatal level of hypertonicity. Ice formation in the IC liquid is also fatal to the cells, since intracellular ice nucleates preferentially on the membrane and irreparably damages it. Successful freezing of erythrocytes, spermatozoa, cornea, and skin has resulted from alloying with what is blithely called a Cryoprotective Agent (CPA). The typical CPAs such as glycerol and dimethylsulfoxide ameliorate the salt segregation in both the EC and IC liquid, replacing some of the salt segregation with less toxic CPA segregation. They form deep eutectics in the ternary water-salt-CPA systems and promote glass formation, just as is the case for metallic glass forming alloys. The method of optimizing the CPA level to lessen salt segregation and avoid IC ice nucleation has proven successful in cryopreserving single cell type systems. However, all attempts at cryopreserving multicell type systems such as organs have failed. An alternative approach is rapid nonequilibrium freezing, which I studied for metal alloy systems while I was Professor Flemings student. If a glass can be formed in the EC liquid as well as the IC liquid, the cells should be undamaged. We have formed glasses in glycerol perfused rat kidneys by quenching at 100°C/s. Our results on ternary liquid systems indicate that human kidneys might be cryopreserved by rapid quenching to form glasses.

11:25 AM Keynote

For the Control and Utilization of Nonmetallic Inclusions: *Tooru Matsumiya*[1]; [1]Nippon Steel Corporation, Adv. Tech. Rsch. Labs., 20-1 Shintomi, Futtsu-city, Chiba 293-8511 Japan

In order to predict the chemical compositions of nonmetallic inclusions, which affect properties of steel products, mathematical models have been developed for computational simulations. Thermodynamic equilibrium is assumed between the nonmetallic inclusions and liquid metal before and during solidification and at the solid-liquid interface as well. Multi-component thermodynamic equilibrium is analyzed by the use of SOLGASMX and Thermo.Calc. Brody-Flemings microsegregation treatment modified by Clyne-Kurz is applied to obtain the solute concentrations in the residual liquid. Pushing-out of inclusions at solidification front is modeled in various ways. Following are examples of the applications of the computer simulations for the control of nonmetallic inclusions. Manganese sulfide precipitates in spot-like segregation, which appears in the centerline segregation in the slabs of anti-hydrogen-induced-cracking steel for natural gas line pipe, are elongated and become film like shape by hot rolling and act as the initiation sites of HIC. Calcium is intentionally added for the prevention of MnS precipitation. By the use of computational simulation this operation was analyzed and it was found that sulfur is mostly scavenged as CaS but MnS precipitates at the very end of solidification of the spot-like segregation when their size exceeds 300 micrometer. It suggests that the reduction of their size by selecting casting conditions is important to properly control the sulfide shape. Deformable inclusions are preferred during hot working for the prevention of cracking. The chemical compositions of primary precipitated oxides in austenitic stainless steels are analyzed as the function of total oxygen content. At the oxygen content of 40 ppm, the oxides mainly consist of alumina and complex oxides such as CaO-Al2O3 and MgO-Al2O3 which have high fraction solid at the hot rolling temperature and is not considered to be easily deformable. On the contrary at the oxygen content of 80 ppm, the oxides contains a lot of SiO2 and MnO which have high fraction liquid at the hot rolling temperature and is considered to be easily deformed. Oxides in steels can also utilized as initiation site of intragranular ferrite (IGF) precipitation, which refines the ferrite grain size and increases the strength and toughness of the products. One of the mechanism of IGF precipitation is considered that MnS precipitation on the oxide inclusions forms Mn depletion zone around it and encourages the ferrite transformation thermodynamically. The mechanism is verified by demonstrating the more the IGF precipitation the larger the Mn depletion, which is changed through thermal history and checked both by calculation and analytical TEM observation. In order to obtain the desired oxides for IGF precipitation sites, the above mentioned computational simulation is also expected to be applied.

RELATED POSTERS:

New Insights on Dendritic Growth: *Martin Eden Glicksman*[1]; Matthew B. Koss[1]; *Jeffrey C. LaCombe*[1]; [1]Rensselaer Polytechnic Institute, Matls. Sci. and Eng. Dept., 110 8th St., CII-9111, Troy, NY 12180-3590 USA

The Isothermal Dendritic Growth Experiments (IDGE) comprise a series of three microgravity experiments designed to study dendrites in pure materials. These experiments permitted telemetry of both real-time still and full gray-scale video images at 30 fps of dendrites growing at different supercoolings. Data extracted from these experiments reveal several novel kinetic features: 1) the dynamic shape of the tip, 2) the time-resolved nature of the growth transients, and 3) the presence of eigen frequencies during steady-state growth. A new microgravity experiment, the Transient Dendritic Solidification Experiment (TDSE), allows fast pressure pulses to modify the free energy available for solidification using the Clapeyron effect. Early TDSE data suggest that the melting point of a dendrite, when subjected to a fast change in growth rate, changes far more slowly than anticipated. Implications of these recent discoveries to dendritic growth fundamentals will be discussed.

An Experimental Method for the Solute Redistribution Dynamics: *Eisaku Tokuchi*[1]; Kimioku Asai[1]; [1]Musashi Institute of Technology, Kobori, 7-4-13 Todoroki, Setagaya-ku, Tokyo 168-0082 Japan

The first experimental investigation for the dynamic solute redistribution in rapid solidification ranged in around hundreds Kelvin/sec average cooling rate, i.e., around 10mm primary dendrite arm spacing, was conducted by using Al-alloy A5052 in TIG (Tungsten Inert Gas) welding. The method was derived from the high speed breaking of thin plate spot welds during its solidification process. The thickness of the liquid film covering the whole breaking surface was directly certified by FE-SEM (Field Emission-Scanning Electron Microscope) observing the cross sections of chemically treated breaking surface liquid film. The liquid film was found to solidify with almost plane solidification front of 0.3 mm-0.1 mm thickness at least. The liquid film was then investigated by small spot XPS (X-ray Photoelectron Spectroscopy) and Ar-ion sputtering to know the electrical element redistribution behavior due to the high temperature oxidation. In the multicomponent alloy which composes Mg with a powerful affinity for oxygen the negative gradient of Mg distribution was the most steep in the air Vs, liquid film interface, gentler in water, and became zero in a solution of surface active agent. Especially, with the result of the third experiment the method could be reached to discuss the solute pile-up in the liquid of moving solid-liquid interface of the cellular dendrite. It was thought that the reason why the result showed almost even solute distribution over the liquid was that the interface concentration tends to be geometrically diluted due to the circular cross sectional interface. The other diffusions driven by interfacial or chemical energy in the liquid behaving essentially as a Al-Mg-Si-Fe quadruple alloy may be also considered.

Cellular/Dendritic Morphology during Unidirectional Solidification of Pb-2.2% Sb: Surendra N. Tewari[1]; *Guolu Ding*[1]; Lu Yu[1]; [1]Cleveland State University, Chem. Eng. Dept., E. 24th St. Euclid Ave., Cleveland, OH 44115 USA

Four Pb-2.2 wt. pct. Sb samples were directionally solidified from the same single crystal seed with its [100] orientation parallel to the growth direction. All four samples were grown for about 10 cm to reach steady state, and then quenched to retain mushy-zone morphology. Three of them were grown with a high thermal gradient of 150 Kcm-1 at growth speeds of 2 mm s-1, 10 mm s-1 and 30 mm s-1 to examine cell, cell/dendrite, and dendrite morphologies respectively. The fourth sample was grown with a low thermal gradient of 40 Kcm-1 and growth speed of 30 mm s-1 to produce well-developed dendrites. The minimal spanning tree (MST) and the Fourier transformation methods were used to perform the statistical analysis of primary spacing and disorder of cell/dendrite arrays. The (m,s)-diagram indicates that disorder of dendrite array can be described by a Gaussian noise applied to an array of hexagonal dendrites. The extent of disorder of the cell/dendrite array becomes smaller when growth morphology changes from cells, to cells/dendrites, to dendrites, and finally to well-developed dendrite. This is also confirmed by the Fourier transformation analysis of the cell/dendrite arrays.

Solidification Behavior of Single Crystal Welds: *J. M. Vitek*[1]; S. A. David[1]; S. S. Babu[1]; [1]Oak Ridge National Laboratory, Mets. and Cer. Div., P.O. Box 2008, Bldg. 5500 MS 6376, Oak Ridge, TN 37831-6376 USA

A model single crystal alloy, Fe-15Ni-15Cr, was used to study the solidification behavior and the grain structure development in weldments. It was found that the dendritic grain orientation, and the substructure pattern defined by regions of dendritic growth in different variants of the preferred <100> cubic growth direction, could be described by considering the competition between alternate crystallographic growth variants. The growth variant whose orientation was most optimally aligned with the heat flow direction was the variant that was selected during solidification. This analysis was applied to welds of single crystal nickel-base superalloys that are used for aircraft turbine blades. The same analysis used for the Fe-Ni-Cr alloys was found to describe the growth behavior in the nickel alloy perfectly. However, unlike the case of Fe-Ni-Cr alloys, the welded nickel alloy showed a strong tendency to form additional, "stray" crystals, which are randomly oriented new grains with no crystallographic relationship to the single crystal base material. The nickel alloys also showed limited eutectic solidification in the inter-dendritic areas. This resulted from solute segregation during solidification. The extent of segregation was successfully modeled with the aid of computational thermodynamics and kinetics analyses. Except for the appearance of stray crystals, the combination of the grain orientation modeling and the segregation modeling allowed for an accurate prediction of the final grain structure and phase distribution in the nickel-base single crystal superalloys. This research was sponsored by the Division of Materials Sciences, U. S. Department of Energy, under contract number DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

Merton C. Flemings Symposium - 2000: Control of Casting Quality

Wednesday PM — Room: Wong Auditorium
June 28, 2000 — Location: Tang Center, East Campus, MIT

Session Chairs: Diran Apelian, Worcester Polytechnic Institute, Worcester, MA 01609 USA; Dixon Chandley, Metal Casting Technology Incorporated, Milford, NH USA; Eisuke Niyama, Polytechnic College Oyama, Oyama-city, Japan

1:45 PM Opening Comments
Diran Apelian, Dixon Chandley, Eisuke Niyama

1:50 PM Keynote
M.C. Flemings Contributions to Solidification Processing Science and Practice: *Harold D. Brody*[1]; Andreas Mortensen[2]; Reza Abbaschian[3]; [1]University of Connecticut, Dept. of Metall. and Matls. Eng., Storrs, CT 06269-3136 USA; [2]Swiss Federal Institute of Technology, EPFL, MX-D121, Lausanne CH-1015 Switzerland; [3]University of Florida, Dept. of Matls. Sci. and Eng., Gainesville, FL 32611-6400 USA

Professor Merton Flemings has made pioneering contributions in each of the areas of solidification science and engineering that is the title of a major session of this Symposium. The research he has conducted with numerous students and coworkers has reshaped the way researchers and practitioners think about the phenomena of alloy solidification, uncovered and exploited basic phenomena, and given birth to new branches of industry.

2:25 PM Keynote
Premium Quality Castings for Aerospace: *Neil Paton*[1]; [1]Howmet Research Corporation, 1500 S. Warner St., Whitehall, MI 49461-1895 USA

The aerospace industry has used premium quality castings for many years, in large part because many of the high temperature alloys used in turbine components can only be produced economically by casting. Recent advances in casting technology have greatly expanded the applicability of castings in aerospace. These advances include improved casting quality, improved dimensional accuracy, microstructural control, and mechanical property control, to the point that castings are now being applied to critical load carrying structures in both military and civil aircraft. The foundation for these significant advances has been laid by a cooperative effort between industry, universities and government agencies. This paper will enumerate some of these advances with specific emphasis on quality improvement, microstructure control and process modeling.

3:00 PM

Synergetic Effect of Rapid Solidification and Mechanical Milling on the Structures and Mechanical Properties of Al-Si Based Alloys: *Junichi Kaneko*[1]; Makoto Sugamata[1]; Yoshiaki Kawaguchi[1]; [1]Nihon University, Coll. of Indust. Tech., Izumi-cho, Narashino, Chiba 275-8575 Japan

With the aim of obtaining property improvements of Al-Si based casting alloys, rapidly solidified (RS) flakes prepared by gas atomization and splat-quenching were mechanically milled (MM) by using an Attritor ball mill with addition of methanol as the milling agent. Both RS flakes and MM powders were consolidated to the P/M materials by hot extrusion. A synergetic effect of RS and MM has been observed in all the tested alloys and the P/M materials showed remarkably high tensile strength. The strength increase by RS was in correlation with the total amount of alloying elements forming second phases. The strength increases by MM were larger than those by RS. The highest tensile strength attained by synergetic effect of RS and MM was 776MPa for JIS AC8A (ASTM 336.0) alloy. High strength observed in these materials can be explained by highly work hardened substructures stabilized by fine dispersoids formed during MM.

3:10 PM Break

3:25 PM Keynote

Optimizing Processing for Quality Castings: *Colby (Dick) Chandley*[1]; [1]Metal Casting Technology Incorporated, 343 State St., Rochester, NY 14650-1106 USA

Early work in aluminum and magnesium by Flemings and co workers showed the importance of control of metal flow and turbulence in producing nonferrous castings without harmful nonmetallic inclusions. Many years later, it was concluded this was of major importance in ferrous metals, even when cast under high vacuum, as well. Counter-gravity filling by pressurizing melts was shown to have advantages in fillout of castings as well as controlling turbulence. Later, vacuum was more widely used to control flow and improve metal quality. the author reviews some of the latest methods of metal flow control, which was so necessary to assure high quality metal castings.

4:00 PM

Continuous Casting and Solidification of Small Cross Sections: *Terry F. Bower*[1]; [1]T. F. Bower and Associates, 751 Ridge Rd., Lewiston, NY 14092-1117 USA

Several features of the solidification process in small cross sections of copper base products are discussed. Grain structure, dendrite structure and arm spacing, and defect structure are products of casting conditions and composition, just as they are in laboratory tests or shape castings. The unique conditions of continuous casting produce some unique and interesting structures and problems. Understanding of structure can lead to problem solutions. An example is run terminations. Although there can be a number of reasons for run terminations, they fall into several classes. The most important one is terminations due to “skulling” or solid formation that no longer is a part of the withdrawing casting. There can be many causes of skulling, including impurity induced tearing, heat transfer problems, mold problems, etc., but the result is the same, the casting process stops involuntarily. A review of how this happens leads to the next topic. For obvious reasons continuous of quality casting at desired rates is the objective of most commercial continuous casting operations. There are a number of reasons for casting inadequate quality or poor productivity. These can be classified into several areas. The most important direction for successful casting is prevention of terminations, and prevention of the reasons for terminations. Often the same problems that cause terminations will lead first to poor quality. Therefore, a full understanding of the cause of terminations can help insure successful casting. Desirable solidification mechanisms are outlined, with some indications of what can go wrong that may limit quality or reduce output. Dendrite arm spacing gives an indication of cooling rate at various places in a casting. An analysis of cooling history can lead to an understanding of both desirable and undesirable process operation. A few examples are discussed. Although grain structures can be readily seen in most casting, interpretation of the relationship of cast grain structure to cast history is often difficult; some cases where an understanding was developed are given. Understanding of quality successful continuous casting is not too different in principle from understanding the laboratory and shape casting that we made in our undergraduate and graduate educations. A purpose of this paper is to make this point evident.

4:10 PM

Development of Strip Casting Process at POSCO/RIST: *Hee-Kyung Moon*[1]; Chul-Min Park[1]; Han-Nam Cheong[1]; Cheol-Gyu Lee[1]; Taewook Kang[1]; [1]RIST (Research Institute of Industrial Science & Technology), Strip Cast. Proj. Team, 32 San Hyojadong, Pohang, Kyungbuk Province 790-330 Republic of Korea

The Pohang Iron & Steel Company Ltd. (POSCO) and its technical research and development arm, the Research Institute of Industrial Science & Technology (RIST), have been developing the thin strip casting process since 1989. Two prototype twin roll strip casters were built at the POSCO□s Pohang Works on a pilot plant scale. A number of cast trials have been carried out to verify the suitability of the process for the production of sheets for some specific steel grades. The production-size caster can produce coils of 10-metric-ton cast strip with a width of 1,300 mm and a typical thickness range of 1.8 to 6mm. The engineering aspects of pilot strip casters, operational overview of casting trials, key technologies, quality of products, and future plan for POSCO/RIST strip casting process are presented.

4:20 PM Keynote

Current Quality Needs for Castings in Automotive: *Sergio Gallo*[1]; [1]Teksid Direzione, Via Pianezza, Torino 123-10151 Italy

Following the oil crisis in the 1970□s and consumer awareness of the great harm caused to the environment by motor vehicle emissions, automakers began to overhaul their design criteria with a view to reducing fuel consumption. One of the many solutions adopted has been the extensive use of aluminum and magnesium alloys instead of steel and cast iron. This has resulted in great weight savings and hence a reduction in fuel consumption. It has also given foundries access to new and attractive markets. In the first substantial applications, namely the fabrication of aluminum cylinder heads and engine blocks, quality requirements were primarily concentrated on static strength and water and oil tightness, in addition, of course, to dimensional precision. New and important uses are being found for aluminum alloys: steering knuckles and suspension links, levers and cross-members. For these new families, the main quality requirements relate to fatigue and impact resistance. New alloys and new manufacturing processes are necessary to ensure that suspension components are endowed with these qualities. Fundamental advances in this field have stemmed from the work of Merton Flemings on alloy metallurgy and casting methods, especially rheocasting. An HIP process known as liquid hipping perfected in conjunction with Metal Casting Technology Inc., Idra Presse and Teksid with the aid of Merton Flemings is now coming on stream. It ensures quality levels and trimmed costs unobtainable with conventional processes. Magnesium, too, is making headway as a replacement for steel in the production of bodywork components. In this case, quality requirements are centred on impact resistance (as shown in crash tests) and corrosion resistance.

4:55 PM
Mold Temperature Measurements of Semi-Continuous Slab Casting for Copper Alloys and Influence of Operating Variables: *Michiharu Yamamoto*[1]; Tomoji Mizuguchi[1]; [1]Nippon Mining and Metals Company Limited, 1-1-2 Shirogane-Cho, Hitachi-Shi, Ibaraki 316-0056 Japan

The mold of a continuous casting plays a important role for products quality and its yield. Depending on its design, operation and maintenance, a continuous casting machine may produce slabs exhibiting surface defects, such as longitudinal or transverse facial cracks, deep oscillation marks and break-out. In steel making, numerous investigations in regard to the measurements of the mold temperatures and heat fluxes, coupled with the mathematical modeling, have been conducted in conjunction of the reduction of oscillation marks and the prevention of break-out. In the slab casting of copper alloys, casting conditions, such as casting speed and temperature of molten metal in the mold, and those physical properties are quite difference from those of steel. Therefore, the temperature fields in slab mold were measured for the semi-continuous casting of copper alloys in order to understand how operation variables affect on the mold temperature. The slab mold was installed with a total of 23 copper/constantan thermocouples embedded in the copper plates at several location. Casting speed , mold fluxes, pouring temperature of molten metal (superheat) , and mold taper of narrow face were selected as operating variables, affected on qualities of cast slabs. Mold temperatures and those fluctuations during casting were characterized from the signals of the respective thermocouples and evaluated with the difference of operating variables. Mold temperatures at the steady-state during casting were compared with those of the different positions embedded in the mold as a function of average temperature and temperature fluctuation.

RELATED POSTERS:

The Effect of Dendritic Structure on the Scatter of Fracture Toughness of Heavy Section Steel Plates: *X. Jie Zhang*[1]; Robert L. Tregoning[1]; [1]Naval Surface Warfare Center, Carderock Div./Code 614, 9500 MacArthur Blvd., West Bethesda, MD 20817-5700 USA

The solidification process can cast long-lasting effects on the property and performance of steel products through its role in defining the chemical and micro-structural homogeneity as well as the overall inclusion characteristics of steel. In quenched and tempered heavy section steel plates, carbide banding structure shows traces of segregation associated with dendritic solidification and is considered to be a main source attributing to the large scatter of fracture toughness. In this study, the effect of carbide band variability on the toughness of heavy-section A533B steel plates has been quantified. Material was removed specifically from densely and lightly banded regions of a A533B steel plate. Half of the material was evaluated in the as-received condition while the remainder was diffusion annealed in an attempt to homogenize the local carbide band density while retaining the global plate properties. Toughness testing was then performed to determine the cleavage initiation toughness (KJc) distribution for each unique material condition. Stereo-section fractography (SSF) was utilized to relate the critical microstructural feature to the associated cleavage initiation toughness. It is found that the lightly banded region in the as-received material exhibits higher toughness than the densely banded material. Diffusion annealing does significantly reduce this toughness scatter while retaining the global plate properties. Weibull statistics within the Master Curve framework provides an accurate description of cleavage initiation toughness in the diffusion annealed material, but the as-received material illustrates more material inhomogeneity than is assumed in this approach. This underscores the importance of considering material inhomogeneity when analyzing material using this approach.

Effect of Strontium Modifiers on Porosity in Cast Al-Si Alloys: *Seetharaman Sridhar*[1]; Peter David Lee[1]; [1]Imperial College, Matls. Dept., Prince Consort Rd., London SW72BP UK

The effect of strontium on porosity formation in aluminium-silicon alloys is not well understood and there is no consensus upon the reason for the effects observed. This paper describes a series of experiments where the effect of adding strontium on pore formation was observed directly with combination of traditional temperature gradient stage and real time micro-focus radiography. These in situ observations provide a new insight into the effect of strontium on the nucleation and growth kinetic of porosity. The addition of strontium was found not to have a strong effect the growth of the pores in the mushy zone. However, strontium was found to have a strong effect upon the oxide structure and its ability to nucleate and stabilise hydrogen bubbles within the melt. The interaction of strontium with titanium-boride grain refiners was also studied, indicating a very strong effect upon the nucleation and stability of hydrogen bubbles formed.

Merton C. Flemings Symposium-2000: Interdendritic Fluid Flow

Thursday AM — Room: Wong Auditorium
June 29, 2000 — Location: Tang Center, East Campus, MIT

Session Chairs: Thomas Piwonka, University of Alabama, Tuscaloosa, AL 35487 USA; David Poirier, University of Arizona, Matls. Sci. and Eng. Dept., Tucson, AZ USA

8:15 AM Opening Comments
Thomas Piwonka, David Poirier

8:20 AM Keynote
Permeability of Flow of Intergranular Liquid in Equiaxed Alloys: *David Poirier*[1]; J. C. Heinrich[2]; R. Erdmann[1]; M. Bhat[3];

[1]University of Arizona, Matls. Sci. and Eng. Dept., AME Bldg. 119, Tucson, AZ 85721 USA; [2]University of Arizona, Dept. of Aero. and Mech. Eng., Tucson, AZ 85721 USA; [3]General Electric, Indust. Control Sys.

Permeability is a key property in the modeling of transport phenomena in the solidification of dendritic alloys. The models are used in computer simulations to predict defect formation in solidifying alloys, such as macrosegregation and microporosity. Flemings, as in so many areas of materials processing, was a pioneer in pointing out the importance of using transport phenomena to understand solidification, and he and Piwonka measured permeabilities for the first time in 1966. In this paper, the permeability for the entire range of volume fraction liquid during equiaxed solidification is estimated, with the specific area of the solid selected as the characteristic length scale of the microstructure. A function for the permeability is based on combining empirical data and calculations into a regression that can be used in computer simulations of dendrite solidification. The permeability for flow of intergranular liquid by fixed equiaxed grains in microstructures was calculated for volume fraction of liquid in the range of 0.40 to 0.932, in order to augment empirical data which are restricted to volume fraction of liquid less than 0.48. A method of processing the images of the microstructures and building a finite-element mesh was adopted to effect the calculations of two-dimensional flows. Permeabilities extracted from the two-dimensional flows are corrected for three-dimensional flows by deducing the ratio of the permeabilities for two-dimensional flows past the circles formed by a plane intersecting randomly placed spheres. For the fractions of liquid approaching one, permeabilities are calculated from sedimentation experiments on model dendrites.

9:00 AM Keynote

Modeling of Macrosegregation: Past, Present, and Future: *Christoph Beckermann*[1]; [1]The University of Iowa, Mech. Eng. Dept., 2412 SC, Solid Lab., Iowa City, IA 52242 USA

Modeling of macrosegregation has experienced explosive growth since the pioneering studies of Flemings and coworkers in the mid-1960s. A review of these early contributions is followed by several examples of more recent studies where generalized versions of Flemings macrosegregation model have been applied to industrial casting processes. The successes and shortfalls of the models in predicting measured macrosegregation patterns are highlighted. Advanced macrosegregation models that include a detailed consideration of the solidification microstructure are reviewed next. Model results are presented that illustrate the profound effects of combined solid movement and melt convection on macrosegregation. Important issues deserving future research attention are identified.

9:40 AM

Liquation and Solidification in the Partially Melted Zone of Al-4.5Cu Welds: Chen Che Huang[1]; *Sindo Kou*[1]; [1]University of Wisconsin, Matls. Sci. and Eng. Depts., Eng. Rsch. Bldg., 1500 Engineering Dr., Madison, WI 53706 USA

Aluminum welds are known to be susceptible to hot cracking during welding and ductility loss after welding in the partially melted zone (PMZ), which is a narrow region immediately outside the fusion zone. Al-4.5Cu alloy was prepared by casting and heat treating. It was welded by the gas-metal arc welding process using a 2319 (essentially Al-6.3Cu) filler wire. The microstructure was examined in the PMZ by optical and electron microscopy, and the Cu concentration distribution was determined across the grain boundary (GB). Liquation was observed both along GBs and at isolated points within grains. The GB liquid solidified first into α (Al-rich phase) and then eutectic. The GB eutectic, mostly divorced, delineated the new GB. Solidification was directional upward and toward the weld regardless of the position of the GB with respect to the weld. This indicates that GB solidification was under the influence of the high temperature gradients in the PMZ. Significant Cu segregation was observed from about 4 wt % at about 10 µm from the GB to about 35 wt % at the GB. The as-cast material was also welded. Liquation was observed along GBs and at prior interdendritic sites. During welding, the interdendritic eutectic melted at the eutectic temperature. As the temperature went above the eutectic temperature, the surrounding α matrix also melted and the liquid became hypoeutectic. Upon cooling, it solidified first as α and then as eutectic, resulting in a eutectic particle embedded in a drop-like α of low Cu content.

9:50 AM Break

10:05 AM Keynote

Study and Modeling of Hot Tearing Formation: *Michel Rappaz*[1]; J. -M. Drezet[1]; [1]Swiss Federal Institute of Technology, Lab. de Metall. Phys., MX-G, Lausanne CH-1015 Switzerland

As for most of the topics in the field of solidification, Mert Flemings has always pioneered new ideas. Hot tearing, a complex mechanism which involves deformation of the coherent and non-coherent solid skeleton as well as flow of the interdendritic liquid, follows also this "first principle"! About 30 year ago, Mert Flemings, in collaboration with S. Metz, devised an interesting shearing equipment in order to test the mechanical resistance of aluminum alloys in the semi-solid state. They explained the influence of grain size, shearing rate, microstructure morphology, volume fraction of solid in terms of particles bonding/debonding, grain sliding and rearrangement. One of the first conclusions outlined in this contribution was that processing of metallic alloys in the semi-solid state should be feasible with various advantages. As a matter of fact, a very similar equipment has been used recently by St John and his group to study the initial rupture of semi-solid metals. As Mert Flemings and his group focused their attention toward semi-solid processing, prediction of hot tearing did not progress much. For many years, the main criterion applied to characterize the Hot Cracking Sensitivity (HCS) of an alloy was based on the solidification interval: the HCS increases with the width of the mushy zone. Feurer, maybe inspired by the work of Flemings and Piwonka on porosity, tried to derive a criterion based on the pressure drop of the interdendritic liquid, but only driven by solidification shrinkage. Clyne and Davies recognized the fact that hot tearing occurs in a critical region of the mushy zone where the film of interdendritic liquid is more or less continuous (i.e., brittle) and the permeability is low. They derived a HCS criterion based on a critical time spent by the mushy zone in the late stage of solidification. More recently, we have derived a very simple model for HCS similar to the Niyama criterion developed for porosity formation, but accounting also for strain-induced flow in the mushy zone. Although the model for the transition between the coherent and non-coherent regions of the mushy zone is fairly crude, it allows to determine the maximum strain rate that an alloy can sustain before a first pore nucleates. On the other hand, in-situ observations on organic alloys grown under Bridgman conditions and deformed in the transverse direction have allowed to directly visualize the formation of hot tears. It was confirmed that hot tearing is indeed intergranular, that it occurs at a late stage of solidification and can be favored by the presence of pores. These in-situ observations have also allowed to better understand the presence of spikes in the ruptured surface of metallic alloys. This paper will review past contributions to hot cracking, in particular that of Mert Flemings, and present our recent model and observations in this field.

10:45 AM

Measurement and Application of Mushy Zone Mechanical Properties in Predicting Aluminum Alloy Ingot Cracking Tendency: *Men-Glen Chu*[1]; Alvaro Giron[1]; [1]Alcoa Technical Center, Ingot and Solid., 100 Tech. Dr., Alcoa Center, PA 15069 USA

The difficulty in predicting the stress development and deformation during casting of an aluminum alloy ingot is that experimental data describing the mechanical behavior in the mushy zone of alloys of interest is not readily available. In addition, published data describing the complete constitutive equation for specific alloys is hard to find. In the absence of reliable data, or for that matter any data, the researcher sometimes is forced to assume that the high temperature behavior of an alloy extends into the mushy zone up to the coherency temperature. The coherency temperature is defined as the temperature above which, for modeling purposes, the alloy is treated like a liquid and below which it is treated like a solid. Furthermore, a fracture criterion is also often not available in the literature. Without this information, it is not possible to predict if a crack will occur for a given stress and deformation during casting. This paper describes our approach used for measuring the mechanical properties of commercial aluminum alloys at temperatures ranging from 200°C to coherency temperature. The strain rate used in the tensile measurements in this work ranges from 0.003 to 0.09 s-1. A constitutive model which is based on the measured mechanical behavior within the mushy zone of a commercial aluminum alloy has been used to estimate the stresses and deformations in an ingot during the early stages of the direct-chill casting process. In addition, experimentally collected data on the fracture strain of the alloy is used to determine the potential for cracking at specific locations in the ingot.

10:55 AM Keynote

Microporosity: *Thomas Piwonka*[1]; [1]University of Alabama, P.O. Box 870202, Tuscaloosa, AL 35487 USA

Microporosity occurs when feed metal is prevented from reaching interdendritic areas in the casting where shrinkage is occurring. It is caused by a combination of shrinkage and gas evolution, and is a particular foundry problem for mushy-freezing alloys, such as aluminum alloys, although it also occurs in ferrous castings. Four decades of modeling and experimental work on the subject have clarified much about the problem. However, the results of this work indicate that current metalcasting techniques are generally deficient in preventing the occurrence of microporosity in commercial castings unless heroic methods are used. This paper reviews the history of the study of microporosity and the results achieved thus far, and suggests where effort might be spent to cure the problem.

11:35 AM

Prediction of Microporosity Distributions in Aluminum Alloy Castings: *Srinath Viswanathan*[1]; Adrian S. Sabau[1]; Qingyou Han[1]; Andrew J. Duncan[2]; [1]Oak Ridge National Laboratory, Mets. and Cer. Div., Bldg. 4508, MS 6083, Oak Ridge, TN 37831-6083 USA; [2]Westinghouse Savannah River Company, Savannah River Tech. Ctr., Aiken, SC 29808 USA

The microporosity size and distribution determines the mechanical properties, notably the ductility and fatigue life, of structural aluminum alloy castings. As part of a program to develop optimized tooling for the design of the casting process for structural aluminum alloy components, models have been developed for predicting microporosity distribution. The permeability of interdendritic liquid in the mushy zone was evaluated, and the measured permeabilities were related to the solidification microstructure. A comprehensive methodology taking into account solidification, shrinkage-driven interdendritic fluid flow, hydrogen precipitation, and porosity evolution has been developed for the prediction of microporosity fraction and distribution. The models are implemented in a computational framework consistent with those of commercial casting codes, allowing them to be easily incorporated in commercial casting simulation software. The predictions from the model are validated by comparison with measurements on test castings as well as a production automotive component.

RELATED POSTERS:

Deformation Behavior of Steels in the Mushy State: J. Horsky[2]; *Ampere A. Tseng*[1]; Miroslav Raudensky[2]; P. Kotrbacek[2]; [1]Arizona State University, Manu. Instit., P.O. Box 875106, Tempe, AZ 85287 USA; [2]Technical University of Brno, Fluid Flow and Heat Trans. Lab., Brno 61669 Czech Republic

Semisolid or mushy-state processing permits a material to partially solidify before shape making operations. The understanding of material behaviour at the mushy state is critical for better control of various semisolid processes. The aim of the present study is to experimentally quantify the deformation behaviours of steel in mushy states. Semisolid specimens under the indentation and upsetting deformation were evaluated at various forming speeds and mushy states. The temperature histories of specimens were also measured to correlate the solid or liquid phase content. It has been found that the deformation resistance of the steel at mushy state was dependent on the deformation rate and the solid phase percentage. The relaxation of steel and force reduction at mushy states were also observed and discussed.

Modeling of Macrosegregation during Casting of HY/HSLA-100 Steel Ingots: *S. Sundarraj*[1]; G. A. Miller[1]; [1]Concurrent Technology Corporation, 100 CTC Dr., Johnstown, PA 15904 USA

Heavy-gage steel plates used in aircraft carriers and submarines are produced by hot-rolling statically cast HY/HSLA-100 ingots. Some problems encountered in producing these plates include: (1) inadequate through-thickness ductility values and carbon segregation/pickup during casting, necessitating a costly pre-heating step before welding. For both problems, knowledge of the composition variation due to macrosegregation of alloying elements provides insight concerning the degree to which the ingot mold type and cropping practice can be used to mitigate those problems. Numerical modeling has become a viable tool for analyzing macrosegregation occurring in static and continuous casting processes. This paper presents a 3-D model of a static ingot casting process. The model describes heat transfer, fluid flow, and macrosegregation of elements such as C, S, Cu, and Nb during casting of HSLA-100 steel ingots. The present model predictions of centerline carbon segregation are compared with model predictions of Gu and Beckerman [Met Trans. A, 30A (1999) pp.1357-1366] and with experimental results for a large 0.41 wt % carbon steel ingot. Numerical predictions of sulfur are also found to be in agreement with measured values for this ingot. This model is used to simulate macrosegregation behavior in HSLA-100 ingots. To determine the compositional variations in the resulting heavy gauge plates, the ingot macrosegregation predictions are transformed to account for deformation during plate rolling. Sensitivity studies are conducted to determine the effect of ingot type, i.e., big end up vs. Big end down, and cropping practice in the resulting heavy gage plates.

Suppression of Channel Segregation in Solidifying Pb-Sn Alloys via Applied Magnetic Field: *Michael Bergman*[1]; [1]Simons Rock College, Phys. Dept., 84 Alford Rd., Great Barrington, MA 02130 USA

Channel convection through the porous, dendritic mushy zone in solidifying alloys results from a non-linear focusing mechanism whereby liquid enriched in the solid melts dendrites as it convects away from the solid. The local melting reduces the parameterized (Darcy) viscous force and increases the flow speed to form a convective channel. However, it has been predicted that an applied magnetic field might prevent channels from forming, because as the Lorentz force replaces the Darcy force as the primary resistance to flow, the retarding force becomes less sensitive to the length scale of the flow, so that the focusing mechanism no longer operates. In this study it is found experimentally that, as predicted, an applied horizontal magnetic field can suppress channel convection when Qm, the Chandrasekhar number appropriate to a mushy zone, exceeds order one. The non-dimensional number Qm is a measure of the strength of the Lorentz force relative to the Darcy force in the mushy zone and, for a given magnetic field, is much smaller than the analogous Chandrasekhar number Q for the fluid melt since the Darcy force in the mushy zone far exceeds the viscous force in the fluid. Previous experimental work failed to find that magnetic fields could suppress channel convection because, although Q exceeded order one, Qm did not. For experiments with a smaller cooling rate, and thus a larger permeability and larger mushy zone Rayleigh number Ram, a stronger magnetic field is necessary to suppress channel convection. The longitudinal macrosegregation is not affected by the absence of channel convection, suggesting that such channels are not always primarily responsible for the mass flux between the mushy zone and the melt.

Merton C. Flemings Symposium - 2000: Education and Art

Thursday PM Room: Wong Auditorium
June 29, 2000 Location: Tang Center, East Campus, MIT

Session Chairs: Harold D. Brody, University of Connecticut, Dept. of Metallu. and Matls. Eng., Storrs, CT 06269-3136 USA; David Ragone, MIT, Dept. of Matls. Sci. and Eng., Cambridge, MA USA

1:30 PM Opening Comments
Harold D. Brody, David Ragone

1:35 PM Keynote
M. C. Flemings Contributions to Education: *D. Apelian*[1]; [1]Howmet Professor of Engineering, Metal Processing Institute, WPI, Worcester, MA 01609 USA

Merton C. Flemings impact on the field of solidification and metal casting is paramount; the program of this symposium is certainly a testimonial to his accomplishments. However, what is even more significant is the lasting effect he has had on education at a national level, in terms of strategic directions for the field of materials science and engineering, at MIT through his leadership as Department Head, his global outreach in distance learning, and many more. The development of a generation of engineers, scientists, faculty members his graduate students–is perhaps, most notable. Mert Flemings passion for education has been the keystone of all his work. He has touched and shaped many lives. In this presentation, we will review key milestones, and the lasting impact Merts work has had on the field.

2:10 PM Keynote
Art Casting: *Richard Polich*[1]; [1]453 State Rt. 17K, Rock Tavern, NY 12575-5011 USA

Abstract text unavailable.

2:45 PM Break

Merton C. Flemings Symposium - 2000: Semi-Solid Processing

Thursday PM Room: Wong Auditorium
June 29, 2000 Location: Tang Center, East Campus, MIT

Session Chairs: Sergio Gallo, Teksid Direzione, Turin, Torino 123-10151 Italy; Francois Mollard, Concurrent Technologies Corporation, Washington, DC USA

3:00 PM Opening Comments
Sergio Gallo, Francois Mollard

3:05 PM Keynote

Rheocasting-Industrial Significance: *Kenneth Young*[1]; [1]Vforge Incorporated

The original observations of the rheocast process made in Mert Flemings MIT laboratories in the early 1970s can clearly be identified as the birth of a new metalworking industry now generally grouped as the Semi-Solid Metal (SSM) industry. A key contribution to the development of this new industry was the very early realization of the practical benefits afforded by processing alloys in the semi-solid state and the intense effort to demonstrate those benefits in a readily apparent fashion. This paper reviews the initial concepts first put forward and implemented by Mert and his coworkers, the diverse alternative processing concepts entertained throughout the following 30 years and analyses the survivors. Semisolid processing can today be broken down into two main categories; semi-solid processing, involving specially cast feedstock which is reheated for forming and slurry-on-demand processes. These evolving commercial operations are remarkably similar in many ways to Merts original proposals. In total, commercial SSM processing operations now exist on at least four continents and annual production of SSM aluminum alone is approaching 50,000,000 pounds. More than 10 car lines and several motorcycles utilize SSM components. Practical examples are provided which illustrate how those initial discoveries have translated into tangible commercial and technological benefits and some new applications for SSM processing are briefly reviewed.

3:40 PM

Verification of Rheology Theorems Used in SSM Simulation Software Packages: *Robert Wolfe*[1]; [1]Madison-Kipp

The use of fluid flow (die filling) and heat transfer (solidification) simulation models have become routine design and engineering tools for molten metal casting processes. Similar simulation models have been developed for SSM (Semi Solid Metal) applications. These models are designed to incorporate the unique shear and viscosity properties of the SSM material during mold filling. Traditionally the liquid models have used Newtonian rheology. SSM models have been developed using either the Bingham/Power Law equations or the Internal Variable theory. This paper will be based upon one or more commercially available casting simulation software packages. These software packages have been specifically developed for the SSM process. The progress of the semi-solid metal front through the mold will be investigated by comparing short shots (partially filled mold shots) to the simulation predictions. The simulation results will be analyzed with regard to specific flow characteristics such as discontinuity, splitting, and reknitting of the flow front. Casting defects such as gas porosity and knit lines will also be evaluated. In this analysis, simulation predictions for mold fill and solidification will be compared to the actual production results of a multi-cavity production tool. In addition to the paper, a Power Point presentation will included. The presentation will be supported by an array of sample castings showing the results of a short shot study. Conclusions will then be provided to assess the accuracy of the SSM simulation packages.

3:50 PM

Characterization of Semi-Solid Materials Structure: *Alexander A. Kazakov*[1]; Luong H. Nguyen[2]; [1]St.-Petersburg State Technical University, Steel and Alloys Dept., Basseynaya 37-49, St.-Petersburg 196070 Russia; [2]Netviz Company, Software Dev., 2029 Nothtowne CT, Columbus, OH 43229 USA

The SSF technology is based on the peculiarities of rheological behavior of SSM. In turn, the rheological characteristics depend on alpha solid-solution morphology. Therefore, the characterization and control of alpha solid-solution morphology at each stage of SSF technology are of prime importance for a successful realization of this technology. We developed Thixomet software, which offers direct visualization and measurement of complex structures and 3D relationships. Thixomet performs a total quantitative description of 2D and 3D SSM structures, including 3D parameters of the skeleton structure and the real morphology of the alpha grains. This study revealed that the SSM structure has been totally skeletonized. A multiply connected skeleton of the structure is a key attribute of SSF technology and is an inherent characteristic for all SSM suppliers. Many of SSF technology problems can not be solved without an understanding of the nature of skeleton structure formation and its evolution at all stages of SSM production.

4:00 PM Keynote

Fundamental Aspects of Semi-Solid Processing: *Michel Suery*[1]; [1]Institut National Polytechnique de Grenoble, Ginie Physique et Micanique des Matiriaux, UMR CNRS 5010 ENSPG, 101 Rue de la Physique, Saint-Martin DHeres, BP 46 38402 France

Since the original discovery of Professor Flemings and his coworkers concerning the unusual rheological properties of vigorously stirred tin-lead slurries, a great deal of effort and money has been invested in the development of rheocasting and thixocasting as well as in the scientific understanding of semi-solid processing. This understanding is concerned primarily with the microstructure of semi-solid alloys generated during either partial solidification or partial remelting, with their rheological behavior and with the modeling of this behavior for the purpose of numerical simulation of forming processes. In addition, a better understanding of solidification and subsequent defect formation requires a good knowledge of the rheological behavior of dendritic structures at relatively high solid fractions. On these various aspects, Professor Flemings has greatly contributed to the present understanding so that the first aim of this paper will be to reference his pioneering contributions. The second objective will be to present the current understanding concerning microstructural and rheological characterizations of semi-solid mixtures together with the latest developments in modeling. Our own recent results and a brief outline of the key problems which remain to be solved will finally be presented.

4:35 PM

Rheology of Semisolid Metal Suspensions: *Andreas N. Alexandrou*[1]; [1]Semisolid Laboratory/MPI, WPI, 100 Institute Rd., Worcester, MA USA

The importance of processing of metals in semi-solid state is increasing rapidly. The main characteristics of the process is a specially prepared alloy with globular microstructure that is processed while in its mushy state. The advantages of semi-solid processing are well documented. The theoretical understanding of the material rheology during flow is still at its early stages. Experiments indicate that in steady flows, semisolid materials exhibit shear-thinning behavior. However, more recent experiments indicate that in rapid transients the material behavior is shear thickening. In addition, experiments show that the slurry can resist a finite stress before deformation. The discrepancy between experiments is due to the rheological complexity of the slurry. In mushy state the mixture is a dense suspension of liquid metal and solid particles. The mixture□s dynamic response during forming is the result of the combined effect of liquid-solid, and solid-solid interactions. The structure adjustment to a given stress is a kinetic process defined by a characteristic time, thus introducing time-dependence in the flow response. Therefore, the material behaves differently under slow and rapid transients. The observed finite yield stress is the result of complex particle-wall and particle-particle interactions. The effective use of the process presumes good knowledge of the material behavior. In this presentation, we will review the current understanding of the rheology of SSM slurries and discuss in detail the modeling of the thixotropy of SSM slurries. Results will be shown for filling simulations at different flow and process conditions.

RELATED POSTERS:

Numerical Model and Experimental Analysis for Die Casting Semi-Solid A356 Alloy: *S. Koller*[1]; C. A. Loong[1]; A. L. Azzi[2]; F. Ajersch[2]; S. Turenne[2]; A. Beaulieu[2]; [1]Industrial Materials Institute, Nat. Rsch. Coun., 75 Boul de Mortagne, Boucherville, QC J4B6Y4 Canada; [2]Ecole Polytechnique, C.P. 6079, Succ. Centre-Ville, Montreal, QC H3C3A7 Canada

A three dimensional finite element model has been developed in order to simulate the flow of semi-solid A356 alloy in the die casting of an experimental 2 kg box type component of varying geometry and wall thickness. The Navier-Stokes and energy equations were solved to predict the filling of the mould as a function of the processing temperature. The evolution of the apparent viscosity as a function of temperature, solid fraction and shear rate was obtained from previously measured rheological characteristics and the results were expressed in the form of constitutive equations. A Buhler SC N/53 real time shot control die casting machine was used to carry out the validation experiments. The test die was instrumented with numerous sensors used to monitor the casting parameters such as pressure, temperature and the flow front filling profile. Comparison between the numerical simulation and experimental results are presented.

Viscosities of Semi-Solid Aluminum Alloys and Composites: Zhijing Zhang[1]; *Ramana G. Reddy*[1]; Srinath Viswanathan[2]; [1]The University of Alabama, Metall. and Matls. Eng. Dept., P.O. Box 870202, Tuscaloosa, AL 35487-0202 USA; [2]Oak Ridge National Laboratory, Mets. and Cer. Div., Oak Ridge, TN 37831-6083 USA

The viscosity measurements were carried out on melts of 356 aluminum alloy and Duralcan MMC-a 380 aluminum-alloy containing 20 volume % SiC particulates under various shear rates at different temperatures using a Brookfield viscometer. Results showed that viscosities of the melts increased with decreasing temperature and decreased with increasing shear rate. These results of the two alloy melts were compared. It was found that both 356 alloy melt and Duralcan MMC melt exhibited similar viscous behavior with respect to shear rate, and the temperature had a more significant effect on viscosity of 356 alloy than that of 380 alloy containing SiC particulates. Based on the present experimental data an empirical viscosity model, which considers the effects of both solid fractions in the melt and shear rate, is proposed.

Physicochemical Forecasting of Semi-Solid Materials Composition: *Alexander A. Kazakov*[1]; [1]St.-Petersburg State Technical University, Steel and Alloys Dept., Basseynaya 37-49, St.-Petersburg 196070 Russia

The fraction liquid-temperature relationship provides the fundamental basis for the design of alloy compositions for Semi-Solid Forming (SSF) technology. Therefore, a search for new Semi-Solid Material (SSM) compositions, as well as physicochemical understanding of the SSF technology processes, is impossible without analysis of the temperature dependence nature of the liquid fraction. This information is obtained from differential scanning calorimetry (DSC) aided by thermodynamic modeling. The estimated results in the current study were obtained using the commercial program ChemSage 4.1 and the thermodynamic database SGTE. The physicochemical composition selection criteria for alloys produced by SSF technology have been developed. The database of critical points for the "fraction liquid-versus-temperature" curves for the commercially important aluminum alloys has been created on the basis of thermodynamic modeling and DSC experiments. The numerical values of the critical points from the "fraction liquid-versus-temperature" curve can be used to optimize the chemical composition of the alloys produced by SSF technology.

Commercial Production of Semi-solid Magnesium Alloy Components: *Stephen E. LeBeau*[1]; Raymond F. Decker[1]; [1]Thixomat, Inc.

Semi-solid processing of magnesium alloys provides a vehicle for enhancing their performance and increasing the utilization of lightweight materials in commercial applications. Thixomolding. produces net-shape parts from magnesium alloys in a single step process involving high-speed injection molding of semi-solid thixotropic alloys. Improvements in the properties of magnesium alloys can be obtained by alloy development and/or controlling the microstructural features viasolidification process control. The mechanical properties and microstructures of Thixomolded. AZ-91D magnesium materials will be presented. Recent developments in new high temperature magnesium alloys will be reviewed in light of increasing demands by the automotive industry. The status of commercial developments will be presented including case studies of semi-solid components

Merton C. Flemings Symposium - 2000: Innovative Casting Processes

Friday AM Room: Wong Auditorium
June 30, 2000 Location: Tang Center, East Campus, MIT

Session Chairs: Andreas Mortensen, Swiss Federal Institute of Technology, Lausanne CH-1015 Switzerland; Toshihiko Koseki, Nippon Steel Corporation, Oita, Japan; Stuart Z. Uram, Certech (Retired)

8:15 AM Opening Comments
Toshihiko Koseki, Andreas Mortensen, Stuart Uram

8:20 AM Keynote
Research and Development of Solidification Processing for High Tc Superconductive Oxides: *Yuh Shiohara*[1]; Teruo Izumi[1]; Yuichi Nakamura[1]; [1]Superconductivity Research Labora-

tory (SRL), Div. IV, 10-13 Shinonome, Koto-ku, Tokyo 135-0062 Japan

It has passed 13 years since discovery of high Tc superconductive oxides (HTSC). Continuous progress on R&D has been achieved and some of them have recently led to its applications. In this presentation, solidification processing and crystal growth of HTSC oxides are reviewed focusing on the progress of solidification processing, understandings of crystal growth mechanisms and developments to applications are discussed. Solidification processes include single crystal pulling, large bulk crystals production, unidirectional solidification for rods, and liquid phase epitaxial thin film growth. Solidification processings are suitable for not only investigating growth mechanisms but for obtaining higher performance, e.g. higher critical currents. This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) as Collaborative Research and Development of Fundamental Technologies for Superconductivity Applications.

8:55 AM

Development of Long Length High Temperature Superconductor Wire for Commercial Applications: *Lawrence J. Masur*[1]; [1]American Superconductor, Two Technology Dr., Westborough, MA 01581 USA

Conductors based on silver sheathed (BiPb)2Sr2Ca2Cu3Ox (BSCCO-2223) are enabling commercialization of High Temperature Superconducting (HTS) wires. Since a breakthrough in their fabrication methodology in 1990, work has focused on improving the supercurrent carrying ability of BSCCO-2223 wires to levels required for practical application. Using a research approach based on understanding the relationships between processing, structure, and properties, and a process development approach based on statistical process control, superconducting performance levels sufficient for practical application have recently been achieved via a reliable manufacturing process. In this paper we will discuss the wire properties resulting from this manufacturing process, and the significant commercial prototypes, such as motors and power cables, enabled by these high performance wires.

9:05 AM Keynote

Growth of Single Crystals with High Perfection: *Georg Mueller*[1]; [1]Universität Erlangen-Nüernberg, Institut fur Metallforschung, Martensstr. 7, Erlangen D-8520 Germany

The title of this talk is identical to the title of a section in chapter 2 of Merton Flemings famous textbook on “Solidification Processing” published in 1974. The paper relates to topics discussed by Merton Flemings, like convective transport phenomena in the melt and thermal stress in the growing crystal, which are still of high relevance for todays production of bulk single crystals by melt growth processes (e.g. Czochralski and Gradient Freeze). Single crystals (Si, GaAs, InP, SiC, etc.) with high perfection are the key materials for electronic industry. Due to economic considerations wafers with a large diameter are preferred, while, because of large-scale integration and decrease of structure sizes, the crystals must be more uniform and should contain less defects. Such improvements of crystal properties are generally achieved by an improved construction of the equipment and optimization of the growth process by large series of parameter variations. In contrast to the time when Merton Flemings published his book, nowadays numerical modelling in addition to experiments has become a very important tool for developing melt growth processes. In this contribution results of computer simulation and experimental validation will be shown for the most important semiconductors and melt growth techniques, Silicon (Czochralski) and GaAs (Liquid Encapsulated Czochralski and Vertical Gradient Freeze).

9:40 AM

Eutectic Solidification of the Al_2O_3-Y_2O_3 System: Itsuo Ohnaka[1]; Yoshiki Mizutani[1]; Nobuhiro Maeda[1]; *Hideyuki Yasuda*[1]; Yoshiharu Waku[2]; [1]Osaka University, Dept. Adapt. Mach. Sys., Yamadaoka 2-1, Suita, Osaka 565-0871 Japan; [2]Japan Ultra-high Temperature Materials Research Center, 573-3, Okiube, Ube City, Yamaguchi 755-0001 Japan

Melt grown Al_2O_3-YAG eutectic ceramics has been taken attention because of high strength up to 2000K. This study presents selection of the eutectic systems and coupled growth of the Al_2O_3-YAG. There are two eutectic reactions in the Al_2O_3-rich portion of the system; the equilibrium Al_2O_3-YAG eutectic reaction (1826°C) and the metastable Al_2O_3-YAP eutectic reaction (1702°C). When the melt was cooled from 2100°C at any cooling rate, it always nucleated below the Al_2O_3-YAP eutectic temperature and then Al_2O_3-YAP eutectic was selected. The Al_2O_3-YAG eutectic was selected when the melt was cooled from 1900°C at a cooling rate less than 1 K/s. The selection of the two eutectic systems was determined by nucleation temperature, although maximum holding temperature of the melt and cooling rate significantly affected the nucleation temperature. Coordination of oxygen and chemical order in melt may affect nucleation behavior. Coupled growth of the system will be also discussed.

9:50 AM Break

10:05 AM Keynote

Undercooled Melts and Rapid Solidification Processing: *Toshihiko Koseki*[1]; Theo Kattamis[2]; [1]Nippon Steel Corporation, Oita 870-8566 Japan; [2]University of Connecticut, 97 N. Eagleville Rd., Storrs, CT 06269-3136 USA

High solidification rates and novel microstructures may be achieved by a rapid heat extraction or a large bulk undercooling prior to nucleation of the solid. Work on the solidification of highly undercooled alloy droplets and large, glass-encased iron-and nickel-base alloy ingots was initiated in the sixties. Large bulk undercooling drastically modified the dendritic and grain structures, as well as solute redistribution. Nucleation and growth of nonequilibrium phases was achieved during solidification of glass-encased highly undercooled droplets. Fully homogeneous nondendritic, supersaturated structures were obtained during solidification of highly undercooled and quenched tin-lead alloy emulsions. Observations of the solidification behavior of levitation-melted, glass-encased nickel-tin, iron-phosphorus and iron-chromium-nickel alloy droplets by high speed cinematography combined with high speed optical temperature measurements confirmed the increase of growth front velocity with undercooling and the decrease in recalescence time with increasing undercooling and decreasing solute content.

10:40 AM

Solidification Structures of Undercooled Melts: *Jinfu Li*[1]; Yaohe Zhou[1]; [1]Shanghai Jiao Tong University, Schl. of Matls. Sci. and Eng., Shanghai 200030 PRC

Cu-30 at% Ni, Fe-7.5 at% Ni and Fe-30 at% Ni alloys are bulk undercooled by glass fluxing to investigate the structural evolution. Two distinct types of grain refinements, occurring at low and high undercoolings respectively, are all observed in Cu-30 at% Ni and Fe-30 at% Ni even if solidification time changes from several seconds to several hundred seconds. Experimental results and theoretical analysis indicate that the grain refinement at low undercoolings is induced by the chemical superheating, while that at high undercoolings by the rapid solidification contraction which leads to the breakdown of the continuous crystal growth. For Fe - 7.5 at% Ni, however, only the first grain refinement is found. The preferential formation of metastable bcc phase at undercoolings higher than 110 K and the subsequent crystallization of stable fcc phase in the coexisting system of bcc solid and the remaining liquid cause a sophisticated change of the eventual structural morphology and size. It is demonstrated that if the bcc dendrites have been broken down before the fcc phase solidifies, the effect of bcc solid stimulating the nucleation of fcc is limited. The majority of bcc phase will be entrapped by the growing fcc phase, and remelted due to superheating, which results in a large grain size. In contrast, the perfect primary bcc dendrite skeleton is favorable for the heterogeneous nucleation of fcc phase, and makes the grain sizedecrease.

10:50 AM Keynote

Rapid Solidification of Fe-Cr-Ni Alloys in Microgravity: *Douglas M. Matson*[1]; [1]MIT, Dept. of Matls. Sci. and Eng., 77 Mass Ave. Rm. 8-407, Cambridge, MA 02139 USA

The study of phase selection during rapid solidification of undercooled Fe-Cr-Ni steel alloys must be accomplished using containerless processing techniques due to the reactive nature of the molten alloy. By using an electromagnetic levitation technique, convection may be varied within limits set by the design of the coil system and operating environment to allow investigation over a broad range of compositions and flow conditions. In ground-based tests, the weight of the sample pulls the specimen into the levitation coils creating significant induced flows within the droplet. In microgravity, convection is reduced and by evaluating the relationship between the sample and the levitation coils, convection may be quantified under steady-state conditions. By manipulating the sample size and induced magnetic field, a wide range of recirculation velocities may be selected independent of the cooling rate. From high-speed digital images of the double recalescence behavior of Fe-Cr-Ni alloys in ground-based testing and in reduced gravity aboard the NASA KC-135 parabolic aircraft, we have shown that phase selection can be predicted based on a growth competition model. An important parameter in this model is the identification of the growth rate of the stable phase into the semi-solid array that formed during primary recalescence. This growth velocity is independent of the initial undercooling relative to the metastable liquidus and is a strong function of the difference between primary ferritic and secondary austenitic recalescence temperatures. By varying the ternary composition, the thermal driving force for nucleation and growth of the second phase may be held constant at different solute concentrations. This work is important in the development of a growth theory to explain how the stable phase interacts with the existing metastable array. A second important parameter in the growth competition model is the delay time between primary nucleation and subsequent nucleation of the stable austenitic phase. This delay time is a strong function of composition and a weak function of the undercooling of the melt below the metastable liquidus. From the results obtained during the MSL-1 mission aboard the space shuttle Columbia, we also know that convection may significantly influence the delay time, especially at low undercoolings. Since the delay time between nucleation of the metastable and stable phases is longer in microgravity, the range of compositions which may be investigated is significantly more broad than that which is possible in ground-based investigations. Future work focuses on identification of the mechanism controlling the formation of a heterogeneous site that allows nucleation of the austenitic phase on the pre-existing ferritic skeleton. By examining the behavior of the delay time under different convective conditions, we hope to differentiate between several of these mechanisms to gain an understanding of how to control microstructural evolution in a commercially important class of structural materials.

11:00 AM Keynote

Solidification Processing of Metal Matrix Composites for the Transportation Industries: *Paul H. Mikkola*[2]; *Tetsuya Suganuma*[4]; *Andreas Mortensen*[1]; *Dale A. Gerard*[3]; [1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Dept. des Mat., EPFL MX-D121, Lausanne CH-1015 Switzerland; [2]Hitchiner Manufacturing Company, P.O. Box 2001, Milford, NH 03055 USA; [3]General Motors Powertrain, Adv. Matls. Dev. Ctr., 1629 N. Washington, Saginaw, MI 48605-5073 USA; [4]Toyota Motor Company, Metall. Matl. Dept., Matl. Eng. Div., Comp. & Sys. Dev. Ctr., 1Toyota-cho, Toyota, Aichi 471-8572 Japan

Metal Matrix Composite (MMC) materials provide combinations of properties, which are of interest in several applications in the transportation industries. Their use in this industrial sector is, however, highly dependent on the simultaneous satisfaction of stringent performance and cost requirements. For this reason, solidification processing, which provides one of the most versatile and economical production routes for this class of materials, is a dominant process class used for the production of MMC materials used in this industrial sector. This article will provide an overview of MMC solidification processing with strong focus on the transportation industries. The two main classes of solidification processes used to produce MMC materials, namely infiltration and stir casting, are briefly described and compared. Focus is then placed on specific applications of MMC□s used in transportation, beginning with a review of current and past worldwide automotive MMC products. We then focus on a few specific applications of MMC□s in the automotive industry, which are used as case studies in a discussion of fundamentals and critical issues in MMC solidification processing as it concerns the automotive industry. These specific applications comprise partially reinforced aluminum-based diesel engine pistons and a petroleum engine cylinder block by Toyota, and extruded particle reinforced aluminum driveshafts by General Motors. We conclude with a case study relevant to the aerospace industry, namely an MMC component used in an airplane brake system.

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Preparation of Cast Iron Ceramic Particle Composites by Compocasting: *Goro Aragane*[1]; Akira Sato[1]; [1]National Research Institute for Metals, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047 Japan

There are strong demands for materials of both high strength and high wear resistance. Composites can be a candidate for the materials. The compocasting process invented at MIT is very suitable to prepare such composite materials. We tried to make cast iron matrix composites containing hard ceramic particles. We made an apparatus composed of an electric resistance heating furnace and two motors rotating a crucible and a stirrer. The crucible is made of Al2O3, the inner diameter 95 mm, and rotated at 0.03 s-1. The stirrer is made of SIALON, one end (40 x 30 x 20 mm), and rotated at 6.7 s-1. The stirrer is located eccentrically in the crucible to stir the semi-solid slurry uniformly. The cast iron of the carbon saturation degree of 0.8 is melted. Ceramic particles of Al2O3 (100, 50, 20 μm),92 ZrO2-8Y2O3 (26μm), TiO2 (20μm) are added onto/into the cast iron semi-solid slurry whose fraction solid at 0.1 - 0.4 under the flow of argon, as 1) powders, 2) powders coated with SiC by CVD, 3) pellets made of iron and ceramic powders, and 4) pellets made of iron, ceramic, and carbon powders. We can disperse uniformly TiO2 powders of good wettability but of a large difference with the cast iron. It is, however, very difficult to disperse not only A2lO3 powders of poor wettability and large density difference, but also 92ZrO2-Y2O3 powders of poor wettability but small density difference. The wettability of ceramic powders is more important than the density difference.

11:45 PM

Structure Dependence of the Viscosity of Semi-Solid A357 Alloys in the High Shear Rate Regime: *Akira Kato*[1]; Anacleto M. de Figueredo[1]; [1]MIT, Dept. of Matls. Sci. and Eng., 77 Massachusetts Ave., Rm. 4-415, Cambridge, MA 02139 USA

Viscosity-structure relations in semi-solid A357 alloys are being investigated under highly transient conditions such as are encountered in actual forming processes, using a modified parallel-plate rheometer. In this rheometer, rapid changes in the shear rate are obtained by abruptly decreasing the plate gap or, alternatively, by increasing the angular velocity of the plate. Alloy slurries are obtained in two distinct ways—by continuously stirring the alloy while cooling it from the liquid state into the semi-solid range or by reheating previously rheocast billets into the semi-solid range. Measurements of semi-solid slurries are made isothermally or during continuous cooling at shear rates up to 2000 s^{-1}. Flow curves measured under conditions of constant and rapidly changing shear rate will be presented and related to the structure of the semi-solid.

11:55 PM

Application of the Drop Forge Technique for Examining Flow Behavior of Semi-Solid Aluminum: James A. Yurko[1]; Merton C. Flemings[1]; [1]MIT, Dept. of Matls. Sci. and Eng., 77 Massachusetts Ave., Rm. 4-415, Cambridge, MA 02139 USA

A "drop forge viscometer" has been designed and built that allows for calculation of viscosity under transient, high shear rate fluid flow conditions of semi-solid metal flows. The viscometer employs a free falling top platen which rapidly compresses a semi-solid sample. Viscosity is calculated by measuring deceleration of the falling platen and using the following relationship: $(-3\mu v^2/2\pi h^5)(dh/dt) = m(d^2h/dt^2)$ where μ is viscosity, v is volume, h is instantaneous height of the sample, and m is mass of the platen. Tests on samples of different thicknesses and under different shear rates have been performed to determine experimental changes in viscosity. The fluid flow behavior of semi-solid metal is not well understood, and the viscosity depends on several variables including shear rate, fraction solid, and thermal treatment time. The apparatus allows for microstructural analysis of compressed samples as a function of these variables. This paper describes in detail how viscosity is determined and discusses the ongoing work here at MIT.

12:05 PM Closing Comments

Harold D. Brody, Stuart Z. Uram

RELATED POSTERS:

Fabrication Process of SiCw/7075 Composite with Uniform Distribution of SiC Whiskers by a Squeeze Casting: *Yoshinori Nishida*[1]; Hiroaki Arima[2]; [1]National Industrial Research Institute of Nagoya, Kita-ku, Nagoya 462-8510, Japan; [2]Dido Institute of Technology (graduate student), Takiharu, Minami-ku, Nagoya 457-8530 Japan

Distribution of reinforcements influences greatly properties of SiC whisker reinforced composite. Then, a squeeze casting process was developed to produce SiC whisker reinforced 7075 composite with uniformly distributed whiskers. SiC whisker preforms were prepared by an aspiration technique using uniformly dispersed whiskers/water solution without binders, to attain uniform distribution of whiskers in the preforms. Infiltration of molten 7075 alloy was carried out using preheated preforms (1023K) by a squeeze casting apparatus with low punch velocity (10mm/s) to suppress compressive deformation of preforms during squeeze casting. Since preheat temperatures of preforms, molten metal (1023K) and mold (523K) were sufficiently high, the compressive deformation were slight. The uniform distribution of SiC whiskers was obtained and proved by the fact that the composites revealed superplasticity after some plastic deformation.

Solidification Processing of SiC Particle Reinforced Magnesium Alloy Composites by Rotation-Cylinder Method: *ShaeKwang Kim*[1]; Young Jig Kim[1]; [1]Sung Kyun Kwan University, Sch. of Matl. Sci. and Eng., 53 3-ga Myongnyun-dong, Jongno-gu, Seoul 110-745 Korea

Mg alloys are gaining increased importance for automotive applications due to their low density and high strength-to-weight ratio. Their range of applications can be further extended if their modulus, wear resistance and elevated-temperature properties can be improved via ceramic particulate reinforcements. The main emphasis is to develop a complete production line in molten state for particulate reinforced Mg alloy composites-manufacturing SiC particulate reinforced Mg alloy composite in the molten state by Rotation-Cylinder Method (RCM, proposed by the authors) and by pouring the resultant composite slurry in suitable moulds. Brute force method such as vigorous stirring by an impeller in an evacuated crucible vessel has been discussed as the most successful method of Al composite slurry formation; simply because nearly all commercially significant reinforcements are poorly wetted by molten aluminum and its alloys. However particulate reinforced Mg composites can be successfully manufactured with moderate stirring by RCM in normal atmosphere. RCM allows the production of U-shaped melt surface, characterized by the stable melt surface with large surface area even in high rotation speed. The characteristic shape of RCM significantly reduces particulate agglomerations and entrapped slags, such that the sound composite can be produced in conjunction with various casting processes. Some indications are included about the viscosity and fluidity of the composite slurry and about subsequent forming processes, especially investment casting and semi-solid process.

Structure and Properties of Alloys Produced by the Ohno Continuous Casting Process: *H. Soda*[1]; A. McClean[1]; A. Ohno[2]; H. Yamazaki[2]; T. Shimizu[3]; [1]University of Toronto, Dept. of Metall. and Matls. Sci., Toronto, Ontario Canada; [2]Chiba Institute of Technology, Dept. of Metall. Eng., Narashino-shi, Chiba-ken Japan; [3]Osaka Fuji Corporation, Amagasaki, Hyogo-ken Japan

The Ohno Continuous Casting process is a unidirectional solidification method which permits the generation of single crystal materials or cast products with a unidirectionally solidified structure. Considerable effort has been expended over the last ten years to cast various metals and alloys including high temperature materials such as Co-based alloys and stainless steel. In this paper, research work which has been carried out at the Osaka Fuji Corporation, and Chiba Institute of Technology, and the University of Toronto is described. Examples are provided of products which are now being manufactured commercially as well as those are being developed.

Thixotropic Behavior of Aluminum Based Alloys and GrANi and ZANi Composites: L. Azzi[1]; F. Ajersch[1]; T. F. Stephenson[2]; [1]Ecole Polytechnique, C.P. 6079, Succ. Centreville, Montreal, QC H3C3A7 Canada;[2]INCO Limited, J. Roy Gordon Rsch. Lab., 2600 Flavelle Blvd.,
Mississauga, ON L5K1Z9 Canada

This study presents experimental results and analytical models of the
rheological behavior of alloys and of complex metal matrix composites developed by INCO Ltd.based on Al-Si and Al-Zn alloys. The composites have been developed for die casting or gravity casting applications with low specific gravity, and improved mechanical properties, specifically for wear resistance. The GrANi alloys are prepared by adding nickel coated graphite particles (100-150) together with SiC or Al2O3 particles to the matrix alloy whereas the ZANi alloys use nickel powders to generate NiAl3 intermetallic particles in situ. The rheological behavior of these material in the liquid and semi-solid state depends on the degree of interaction between the particles of graphite SiC or Al2O3 and the intermetallic NiAl3 phase, all of which contribute characteristics specific to each of the composites. Viscosity measurements were carried out in a HAAKE RV 12 rotating spindle viscometer using a helically grooved or a helical ribbon spindle. In the liquid state thesuspension is very susceptible to sedimentation or flotation of particles. A pseudo-plastic behavior was observed at high shear rate corresponding to a good dispersion of particles. An apparent thixotropic behavior for the ZANi composite is characterized by a hysteresis loop and a yield stress was observed when the sample is sheared after a period at rest. This apparent behavior is attributed to the tendency of the NiAl3 particles to rise to the top of the sample. In the semi-solid state however, the thixotropic behavior is attributed to a structural breakdown of the primary phase particles and is described by an analytical model based on the theoretical approach of Moore and developed further by Mada and Ajersch.Comparison between the composites of increasing degrees of complexity are illustrated in terms of the analytical expressions and are supported by microstructural characterisation.

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