John L. Jorstad, President
J.L.J. Technologies
Richmond, VA

The 8th International Summer School on Aluminum Alloy Technology

Casting and Solidification of Aluminum and Magnesium Alloys

Trondheim, Norway, August 21-25, 2006

Summer school! That sounds like an awful way to spend one's time in late summer while friends and colleagues are achieving new heights hiking mountain trails in Wyoming or challenging monster waves off Waikiki beach or reeling in citation fish in Arkansas or biking the back roads of New England. But this was no ordinary summer school, and the venue was as inviting as many trails, beaches, fishing holes and back roads.

This was the 8th International Summer School on Aluminum Alloy Technology, and the fourth dedicated largely to pouring and solidification of aluminum and magnesium alloy castings. The site was the Pirsenteret Auditorium at the harbor in Trondheim, Norway, with a beautiful view of Munkholmen Island out in the Fjord.

Background

The international summer schools originated in 1997 as a joint project of the Norwegian University of Science and Technology (NTNU) and the Norwegian Foundation for Scientific & Industrial Research, the largest research organization in Scandinavia (SINTEF). They were in Trondheim, Norway, the home of NTNU, and the specialized curriculum was designed to be of interest to the foundry and die casting communities as well as the integrated cast houses that direct chill (DC) cast the base-stock used to make wrought products.

NTNU and Worcester Polytechnic Institute (WPI) enjoy a close cooperation. WPI is the home of the Metals Processing Institute and the Advanced Casting Research Center (ACRC – the university/industry research consortium of which NADCA is a corporate member). Professor Diran Apelian at WPI and professor Lars Arnberg at NTNU are each visiting professors at the other's university. The two institutions collaborate on certain research projects and often exchange students.

Arnberg spent part of his sabbatical at WPI in the late 1990s, and at that time he and Apelian agreed that a summer school for foundries and die casters should be held bi-annually, alternating between the U.S. and Norway — thus began the joint sponsorship of special summer schools dedicated to pouring and solidification of aluminum and magnesium alloy castings. Two such schools have now been held at WPI, in 1999 and 2003, and three at NTNU, in 1997, 2001 and the 2006 school reported herein (the school was not conducted in 2005 because of schedule conflicts with other international events).

Lecturers are invited from around the world, based on their expertise and on their teaching skills. All lectures are provided in English. Students, too, come from around the world — this year's school included students and lecturers from the USA, Norway, England, France, Germany, Italy, Switzerland, Sweden, Austria, Greece and Venezuela.

The summer school was officially opened with a welcome by professor Bjørn Hafskjold, dean of the Faculty of Natural Sciences and Technology at NTNU, who provided an overview of the university and surrounding community. Trondheim was the first capital of Norway and remains its coronation city; the Viking king Olav Tryggvason reigned in Trondheim and is buried beneath Nidaros Cathedral; the city celebrated its 1,000 year anniversary in 1997. Trondheim is truly a university town — its population swells from about 150,000 permanent residents to nearly 180,000 while classes are underway.

The Curriculum

Solidification – Arnberg and Apelian provided a strong basis for the lectures that would follow by thoroughly reviewing solidification fundamentals. Arnberg provided an overview of alloy composition and phase diagrams, crystal types and morphologies, microstructure generation, the effects of alloy concentration, constitutional undercooling and cooling rate, control of alpha dendrites and eutectic phases, growth mechanisms of non-facetted (aluminum and magnesium) and facetted (silicon and intermetallic phases) crystals and structural modification mechanisms.

Most interesting for everyone present, Arnberg showed recently-generated high-magnification x-ray video images taken during solidification of aluminum-copper casting alloys in real time. Arnberg and Dr. Rangvald Mathiesen of SINTEF have carefully studied columnar and dendritic growth and stray crystal formation by synchrotron x-ray video microscopy using the European Synchrotron Radiation Facility in Grenoble, France. Their studies have confirmed and clarified dendrite growth, fragmentation and impingement (coherency) theory and have provided other important insights regarding solidification of aluminum alloys. To view images and to learn more about how they were generated, visit February's issue of LINKS online at www.diecasting.org and follow the link to "X-ray Videos of Dendrite Formation," and also see "X-ray Monitoring of Solidification Phenomena in Al-Cu Alloys" by Mathiesen and Arnberg, published in Materials Science Forum, Vol. 508 (2006), pg. 69-75.

Apelian tied his lectures on solidification fundamentals to net shape processing methods, including the various sand and permanent mold processes, die casting, novel processes such as semi solid and squeeze, ingot casting and growth of single crystals. He guided the class through liquid/solid transformations, heat of fusion, the effects of undercooling, the various reactions and transformations that occur during solidification, liquid state concerns and issues such as hydrogen and inclusions, mold cavity filling methods and precautions, viscosity and dendrite coherency in the mushy region, heat, mass and fluid flow during pouring and solidification, properties, microstructures and defects in solidified parts, thermal treatments of solidified parts and a special perspective on semi-solid metal processing.

Grain Refinement – Professor Lindsay Greer from the University of Cambridge in England provided outstanding lectures on the subject of grain refinement, its benefits, mechanisms and issues. He explained refinement theory and described the various nucleants and their suitability for specific alloys; for instance, the traditional 5:1:Ti:B master alloy used so often to refine aluminum melts is not the most suitable for casting alloys containing significant amounts of Si — sub-stoichiometric AlTiB master alloys are better.

Melt Preparation – Professor Makhlouf Makhlouf from WPI lectured on liquid metal processing. He identified the primary quality detractors, hydrogen, oxides and other inclusions and pointed out their effects on such properties as fatigue performance. He described the various systems and techniques available for removal of hydrogen and oxides and identified equipment and means to assess the cleanliness of melts. He provided explanation for the difficulties metalcasters encountered making sound castings during hot, humid weather and also pointed out the potential adverse effects of various alloying elements on hydrogen solubility and oxidation potential.

Aluminum-Silicon Alloy Modification – Makhlouf also lectured on the Al-Si alloy system that is the backbone of the global foundry and die casting industries. He pointed out the benefits of Si and described the Al-Si phase diagram and the generation of primary and eutectic phases. He provided examples of the acicular, sharp-edged plate-like eutectic structure of an unmodified alloy compared to the fine, coral-like fibrous structure of a well-modified alloy. He also described the chemical versus quench mechanisms for achieving modification, explained the beneficial effects of modification to properties and machinability and warned of potential modification issues, such as increasing porosity and interactions between certain modifiers. He finished by explaining the new theory regarding the mechanism of eutectic modification that has been developed at WPI.

Permanent Mold Casting – John Jorstad of J L J Technologies provided his perspective on the gravity and low pressure permanent mold processes as means to manufacture high integrity castings. He indicated that turbulence is the bane of all such processes but that bottom-filling is the least turbulent mold filling scheme. It is difficult to top fill without exceeding maximum flow velocity guidelines at the start of pour, and the ever-diminishing metal head can create fill and feed issues toward the end of pour. The preferred scenario is therefore either tilt gravity permanent mold or one of the low pressure variations; the traditional low pressure (LPPM) process is used successfully to cast styled wheels and other structural components, and such variations on LPPM as Vacuum Riserless/Pressure Riserless (VRC/PRC) and Counter Pressure (CPC or PCPC) provide improved features especially useful when casting automotive chassis and suspension components in high volume.

Sand Casting – David Weiss from Eck Industries traced the history of sand casting from ancient times to the present and then described the numerous sand casting systems, aggregates and binders in use today. He provided numerous examples of parts cast in sand and explained the reasons for selection of one system over another.

Weiss finished with a viewing of "Ablation Casting," a unique and proprietary process being developed and fine-tuned at Eck together with its originator. The process provides extraordinary solidification rates and exceptionally high mechanical properties and also seems suitable for casting hot-short alloys such as the high-strength compositions usually reserved for wrought applications.

Novel Processes – Jorstad noted the outstanding features of conventional high pressure die casting (HPDC) — the preferred process for 70% of all aluminum and magnesium cast worldwide. HPDC provides near-net-shape, close dimensional control, great detail and complexity, fast casting cycles, minimum or no secondary machining and the lowest-cost scenario for high volume casting production. Still, the turbulent fill typically associated with the process limits it to non-critical applications; die castings blister when heat treated and out-gas when welded. To take advantage of the desirable features and the low cost of HPDC while overcoming its few weak points has required development of some novel approaches, the subject of the lectures by Jorstad.

High-vacuum die casting avoids entrapment of cavity gasses by evacuating the die ahead of turbulent die filling — if no atmosphere is in the die, no atmosphere can become entrapped. Several high vacuum process variations, such as Vacural™ and High-Q-Cast® were described.

Semi-solid casting (SSM) also avoids entrapment of cavity gasses but does so by providing a non-turbulent, stable metal flow front. Several SSM process variations were described, including thixocasting (the billet route), Ube's New Rheocasting process (NRC™) and THT's Sub Liquidus Casting (SLC™) process (both, rheocasting slurry routes).

Rapid Solidification in Die Casting – Professor Wilfried Kurz from the Swiss Federal Institute of Technology in Lausanne provided cooling curve simulations and pointed out that solidification in die castings is often completed in less than one second. Cooling rates are typically 500 - 1,000 K/s and the velocity of the liquid-solid interface is thus also rapid (≈1 mm/s). In this environment, grains are tiny and equiaxed — SDAS is typically 15µ± and eutectic spacing <1µ.

Magnesium High Pressure Die Casting – While billed as a lecture on magnesium die casting, Dr. Haavard Gjestland from Elkem really taught an outstanding course on the HPDC process — principles and issues applicable to aluminum and magnesium alike. He took the process through melting, melt transfer to the shot cylinder, temperature control in the shot sleeve, injection into the die, cooling and solidification under pressures of ≈1000 bar, the effect on microstructures of high pressure and rapid cooling and the benefits of tight shot controls. He demonstrated the benefits of process simulation and explained the complexities of microstructure prediction. He showed the orders of magnitude differences in cooling rates achieved in the shot sleeve, as the first metal strikes the die, as the bulk of casting solidifies and in the biscuit. He related the physical properties of AZ and AM magnesium alloys to performance of the casting process.

Aluminum Casting Alloys – Arnberg covered the families of aluminum castings alloys as differentiated by the Aluminum Association alloy numbering system. He began by tracing the typical solidification path on a phase diagram and identifying primary and eutectic reactions. He explained the alloy features that affect fluidity, porosity formation and hot cracking. He defined the roles of alloying elements and provided an overview of each alloy family.

Magnesium Casting Alloys – Gjestland covered everything from the first commercial production of magnesium in 1886 to the raw material used in modern production, properties of pure Mg, current uses (especially in automotive), design principles, the alloy designation system, microstructure formation, reasons for alloying, the effects of elements on magnesium's reactivity and castability and finally, the properties and uses of the families of magnesium alloys.

Figure 1 *- The lecturers at the 8th International Summer School on Aluminum Alloy Technology.*

Casting Defects – Professor Franko Bonollo from the University of Padova in Italy first differentiated between "defects" (preventing proper function) and "imperfections" (detracting from perfection but not preventing function). He also spoke of the approaches to assessing defects — theoretical (considering the system and predicting cause) versus practical (post mortem examination to determine cause). He provided an overview of defect types and categorized them as either filing defects, solidification defects or defects caused by reactions between melt and molds or dies. He related the presence of defects to the mechanical behavior of cast parts.

Heat Treatment – Professor Oddvin Reiso, research manager at Hydro Aluminum in Sunndalsøra, Norway, spoke of the reasons for post-solidification heat treatment and the effects of heat treatment on microstructures and properties. He explained which alloy families are heat-treatable and the temper designation numbering system. Solution heat treatment or homogenizing re-dissolves low-melting-point eutectics, other useful precipitates and spheroidizes silicon and some other intermetallic-type phases. Quenching entraps solutes and precipitation aging re-precipitates those in a location, precipitate size and distribution that strengthens and hardens the matrix.

Modeling of Solidification Microstructures – Professor Charles-André Gandin from Ecole des Mines in Paris noted that modeling provides direct access to mechanical and physical properties of alloys and to issues such as segregation, porosity, hot tears, cracks and stresses in castings. Modeling is a tool for interpretation of experimental observations, for prediction and improvement of alloys, properties and performance, for visualization of phenomena and events during solidification, for analysis of defects, for better understanding of coupled events and as an exercise for learning. He explained the simulation links between solidification, heat treatments and mechanical properties, the expression of such microscopic scale applications as the lever rule, Scheil equations and local solidification paths and of such macroscopic applications as composition profiles. He then showed several classical examples of process and microstructure modeling.

Modeling of Fluid/Heat Flow and Casting Defects – Professor Hervé Combeau from Ecole des Mines in Nancy, France, provided the conservation and transport equations for single phase (liquid) and mushy-zone conditions and applied those to the pressure drop induced by shrinkage, to macro and micro-segregation, to the Scheil model, etc., and used the tools to predict macrosegregation and microporosity.

Direct Chill Casting – Dr. Gerd-Ulrich Grün from Hydro Aluminum R&D in Bonn, Germany, provided a historical overview and full description of the direct chill (DC) casting of aluminum, the quality criteria for DC cast products, the influence of mold construction and processing parameters on structure and surface features. He also provided a complete overview of modern DC casting equipment, installations, products and performance.

Modeling of Direct Chill Casting – Professor Asbjørn Mo from SINTEF presented the concepts used when modeling the DC casting of aluminum with focus on phenomena at the macroscopic scale and with emphasis on the underlining physics; he avoided discussion of micro-scale phenomena. He detailed the modeling of heat flow, the development of thermally-induced stresses and the formation of defects during solidification. He provided examples of modeled versus experienced thermally-stressed and deformed ingots, surface segregation, hot tearing and microporosity.

Casting Design, Properties and Applications – David Weiss provided the final lectures, correlating application and design features with casting parameters and post-casting treatments to achieve required properties. First, he pointed out the fundamental requirements for strong castings: use a good alloy, make sure it is clean and hydrogen free, use good gating and pouring principles and control solidification rates. Risers are needed to feed solidification shrinkage but they slow solidification — chills increase solidification rates but can cut off feed paths — so the two must act in sync. He sited an A206 alloy final drive housing and a B356 load arm where controlling solidification rate provided properties well above AMS requirements — proof that properties of structural castings are predictable if solidification parameters are defined and followed. Next, he cited heat treatment as a useful tool, used together with chemistry and casting parameters, that can be manipulated to provide needed engineering properties, and he provided high-ductility and high elevated-temperature applications as examples. Finally, he said that hot isostatic processing (HIP) can heal hydrogen and shrinkage porosity in A206 alloy, providing an increase in strength and a very significant improvement in ductility and fatigue performance.

Socializing

As important as the specific curriculum, daily social activities provided students and lecturers alike opportunities to interact, to relate the information provided to specific needs and cases back home and to develop lasting friendships. On the first evening of classes, a get-to-know-one-another reception was held at the Pirsenteret Center, the site of the lectures and daily lunches. The second evening included a boat trip across the fjord to Munkholmen, a prison-fortress built on the island in the mid-1600s. Following a tour and special shrimp dinner, Professor Otto Lohne demonstrated the reproduction of ancient coins, and each student had an opportunity to make a silver coin as a souvenir of the summer school. The next evening, students, lecturers and university notables were the guests of Arnberg and his wife Marie for a reception at their home nearby the university. The final evening was a banquet at the Grenaderen Restaurant, next to Nidaros Cathedral and the Archbishop's Palace.

Next Summer School – 2008 at WPI in the U.S.

The next summer school dedicated to the pouring and solidification of aluminum and magnesium alloy castings is scheduled to be in 2008, probably in August, at WPI in Worcester, MA. As the time nears, watch for the announcement in Die Casting Engineer.

About the Author

John L. Jorstad, president of J.L.J. Technologies, is a consultant in aluminum melt and foundry practices. He spent 36 years at Reynolds Metals Co., mostly in R&D, devoted to the development of the hypereutectic alloy 390, its development, casting, machining and applications in premium engines. Since retiring, he has served as a consultant to the aluminum foundry industry. Jorstad is a member of NADCA, SAE, AFS and ASM International and has served as a national director of AFS and as a director and trustee of FEF. He was elected a Fellow of ASM International, has received NADCA's (SDCE's) Achievement Award, the Nyselius Award and the Gullo & Treiber Award, as well as AFS's Award of Scientific Merit, Hoyt Lecture and Joseph S. Seaman Gold Medal, and he is a past recipient of both the Flemings and Witt awards from the ACRC.