SHAPE CASTING: 4th International Symposium 2011

in honor of
Prof. John T. Berry

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in honor of
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Foreword

It was the spring of 1990 when paths of Prof. John T. Berry and mine crossed for the first time. I was looking for research opportunities in castings in graduate schools. I had written a letter to the Ph.D. supervisor of my father, the late Dr. Voya Kondic, who had then forwarded my request to one of his many former Ph.D. students, John Berry. Prof. Berry was the department head of the Metallurgical Engineering program at the University of Alabama at that time when he sent me a letter and kindly offered me a graduate assistantship. It was an agonizing decision to decide to pursue my M.S. degree elsewhere and it was even more agonizing to send a letter to Prof. Berry informing that I would have to decline his offer. In the letter, I wrote that he would always be my friend and that I hoped to meet him one day. I thought that I had offended this kind man by deciding not to join his program. I could not have been more wrong.

Since 1990, I have had the pleasure of getting to know Prof. Berry, as a scholar, a mentor, a teacher, a leader. His academic accomplishments in many prestigious universities in the United States speak for themselves. The success of his former students, some of whom serve as faculty members and academic leaders, including a university president is even more impressive. Prof. Berry is a role model for any scholar; he has a passion for learning and even a greater passion to share his knowledge with others. He has a unique character that combines a high level of energy and patience for others. Although I never had the pleasure to work with Prof. Berry at the same institution, I feel privileged to know him. He was there for me whenever I needed something from him; data, a recommendation letter, an endorsement, a candid review of a paper. I learned a lot from his published literature on castings. I think that I learned even more from him on how to help others.

This symposium, the fourth in the series, has been organized to celebrate the accomplishments of Prof. Berry as a scholar in castings and solidification, a mentor, an advisor and a friend. The papers included in this volume were recruited to reflect the broad research interest of Prof. Berry.

John, many thanks for all that you have done for the casting world and those who were fortunate enough to have met you. You have made the world a better place.

Murat Tiryakioğlu
December 21, 2010

P.S. The picture on the cover is from the Ph.D. thesis of my late father, Dr. Ergin Tiryakioğlu (University of Birmingham, UK, 1964) who used the results from Prof. Berry’s thesis (1954). This picture, which shows an optimum size feeder, was selected as a tribute to John’s many contributions to feeder dimensioning and was cast in the same laboratory where Prof. Berry conducted his Ph.D. research.
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Symposium Organizers/Editors

Murat Tiryakioğlu is the director of School of Engineering and a Professor of Mechanical Engineering at the University of North Florida. He received his B.Sc. in Mechanical Engineering from Boğaziçi University, M.S. and Ph.D. in Engineering Management from the University of Missouri-Rolla, and another Ph.D in Metallurgy and Materials from the University of Birmingham, England. Dr. Tiryakioğlu grew up in his family’s foundry, which continues to thrive in Istanbul, Turkey. This has led to research interests in process design for high quality castings, aluminum heat treatment modeling and optimization, process-structure-property relationships in metals, statistical modeling and quality and reliability improvement, on which he has written over 100 papers, technical reports and book chapters, and edited 6 books.

Dr. Tiryakioğlu is the recipient of the inaugural John Campbell Medal awarded by the Institute of Cast Metals Engineers in UK. He was selected a TMS Young Leader in Light Metals and was awarded the SME Eugene Merchant Outstanding Young Manufacturing Engineer. He is a member of TMS, and a senior member of ASQ, and is an ASQ Certified Quality Engineer.

John Campbell has retired from his post at The University of Birmingham and his editorship of the International Journal of Cast Metals Research. He keeps in touch, retaining an Emeritus Status at the University.

Since these moves he has mainly occupied himself with practical work in foundries around the world, applying, testing, and extending the latest technology to upgrade quality and reduce costs. Despite some casting successes in which the author is grateful and proud, he has also accumulated a few scrapped castings that confirm the technology of filling castings is still not fully developed.

Thus globetrotting activity constitutes valuable education. However, longer-term updating of existing books and the writing of further books has been delayed, but Castings, 2ed (2003) and Castings Practice (2004), in addition to the proceedings the previous Shape Casting Symposia, all remain bargains! Complete Castings Handbook should appear in 2011, and will be required reading.
Paul N. Crepeau is a GM Technical Fellow in Advanced Materials Engineering at General Motors Powertrain Group in Pontiac, MI USA. He supports aluminum intensive engine programs and leads a multidisciplinary team merging CAE and Materials Engineers to advance structural FEA of automotive components. Dr. Crepeau received his B.S. in metallurgical Engineering at the University of Alabama (1978) and, after a 5-year respite at an iron foundry, both M.S. in Metallurgy (1985) and Ph.D. in Metallurgical Engineering (1989) from the Georgia Institute of Technology. He has published in the areas of fracture mechanics, molten metal processing, quantitative metallography and image analysis, aluminum heat treatment, Monte Carlo simulation of fatigue test methods, and material property database strategy. Dr. Crepeau is a registered professional engineer and former chairman of both the AFS Aluminum Division and the TMS Aluminum Committee. Dr. Crepeau was editor of Light Metals 2003.
Modeling Session

**Daan Maijer** received his B.A.Sc. and Ph.D. in metals and materials engineering from The University of British Columbia in 1994 and 1999, respectively. He is currently the Director of the Integrated Engineering Program and an Associate Professor in the Department of Materials Engineering at UBC. His undergraduate teaching is focused on engineering design taught through project-based learning where groups of 3 – 5 students propose, design, build, and test multidisciplinary projects. As one of the principal researchers in the Materials Processing Group, his research aims to develop insight into the industrial processes used to transform metals; in particular, casting processes, to improve product quality and process productivity. This research often involves the development of mathematical models that capture the complex physical phenomena active in these processes and relies on laboratory experiments and/or plant trials to provide the data necessary for model development and validation. This research is industrially oriented and has led to collaborations with companies within Canada (Alcan International Ltd., Canadian Autoparts Toyota Inc., and Timminco Ltd.) and abroad (Corus, Titanium Metals Corp. and The Timken Co.).

**Mark Jolly** is a Senior Lecturer and Director of Industrial Liaison in the School of Mechanical Engineering at the University of Birmingham, UK. He has run the Castings Centre at the University since 1995. He runs the Process Modeling Group within the school and has been Principal Investigator on more than 15 funded programs in the last ten years valued at over £5M. He was awarded the University of Birmingham Josiah Mason Award for Business Advancement in 2010 and the Institute of Cast Metals Engineers’ Oliver Stubbs award in 2008. Mark is on the Solidification Committee of TMS and a key reader for Met&Mat Trans B and a previous chair of the board of key readers. He also sits of a number of committees for the UKs Institute of Materials, Minerals and Mining namely, Sustainable Development Committee (Vice Chair), Light Metals Board and Materials Science
and Technology Division. He is also on the Institute of Cast Metals Engineers Membership Committee and Education and Training Committee. Mark graduated from the University of Sheffield in 1978 with a Bachelor of Metallurgy and continued his studies at Cambridge University to obtain a PhD in 1982. He then started worked in industry for 15 years for a number of companies in the automotive and foundry sectors in the UK and abroad before moving back into academia in 1995. He has over 280 publications including 4 in energy. These include: 2 Patents, 2 book chapters, editor of 2 conference proceedings, over 50 invited seminars & lectures and over 100 technical reports for industry. Mark is a Chartered Engineer, a Chartered Environmentalist, a Fellow of the Institute of Materials, Minerals and Mining and a Fellow of the Institute of Cast Metals Engineers.

**Solidification Session**

**W. D. Griffiths** is currently Senior Lecturer in the School of Metallurgy and Materials in the University of Birmingham, UK. His research interests involve the study of interfacial characteristics of the metal casting processing process. Research topics to date have included, (i). the prediction of metal-mould interfacial heat transfer coefficients for better modelling of the casting process, (ii). the study of oxide film defects in light alloy castings and (iii). the study of the liquid-metal pattern interface in the Lost Foam casting process. Most recently, research has concentrated on the application of radioactive particle tracking techniques to the study of the behaviour of inclusions during mould filling, (Positron Emission Particle Tracking). To date, over 70 journal and conference papers have been published on these topics. Also, Dr. Griffiths was National President of the Institute of Cast Metals Engineers for 2009-2010, and is currently Chair of the Institute of Cast Metals Engineers Technical Board.
**Peter Schumacher** is Managing Director of the Austrian Foundry Research Institute and holds the Chair of Casting Research at the University of Leoben. He obtained his Dipl. Ing. in 1989 at the University of Braunschweig Germany to continue his education in the UK. He received his by Alcan sponsored Ph.D. in 1994 in Metallurgy and Materials Science at the University of Cambridge U.K and held an Advanced EPSRC Research Fellowship at Oxford University from 1997 to 2002. In his 21 year career in metal casting he has co- and chaired numerous conferences and received the Cook Ablett Award U.K. and the TMS Magnesium Technology Award for his work on grain refinement.

**Process Session**

**Glenn Byczynski** is Manager of Nemak Engineering Centre in Windsor Ontario, Canada. He received his Ph.D. in Metallurgy and Materials Science from the University of Birmingham in U.K. in 2002. His Masters (Materials Science in 1997) and Bachelor’s (Mechanical Engineering in 1994) were conducted at the University of Windsor. In his 18 year career in metal casting he has held several R&D and Engineering positions within Nemak and Ford Motor Company including Research and Development Manager for Nemak’s European Business Unit, based in Germany and Engineering Manager at Nemak’s Windsor Aluminum Plant. He was Chairman of the Detroit-Windsor Chapter of the American Foundry Society (AFS) in 2006-2007, is a director and regional chairman of the Foundry Educational Foundation and is a registered Professional Engineer in the Province of Ontario. He enjoys spending time with his wife and two sons.
Sergio Felicelli has a Nuclear Engineering degree from Instituto Balseiro (Argentina) and a Ph.D. degree in Mechanical Engineering from the University of Arizona. He worked 17 years for the Argentine Atomic Energy Commission, where he was head of the Computational Mechanics Division, and 2½ years for the Crystals Division of Saint-Gobain High Performance Materials in Northborough, Massachusetts. In August 2004, he joined the faculty of the Department of Mechanical Engineering of Mississippi State University, where he is currently a tenured Endowed Professor and a faculty member of the Center for Advanced Vehicular Systems (CAVS). Dr. Felicelli has worked over 25 years in developing numerical models for applications in solid and fluid mechanics, heat transfer, transport processes, and solidification of alloys. He is the author of some of the pioneer works in computer modeling of freckle segregation during solidification, having written 35 journal articles in the area of macrosegregation and porosity defects in solidification processes and a total of 80 peer-reviewed publications during his career.

Methods & Systems Session

Alan Druschitz is the Director VT-FIRE and an Associate Professor in the Department of Materials Science and Engineering at Virginia Tech. He received his PhD in Metallurgical Engineering in 1982 from the Illinois Institute of Technology, Chicago, IL. He was previously a Research Professor at the University of Alabama at Birmingham, a Staff Research Engineer General Motors Research Laboratories and the Corporate Director of Materials R&D Intermet Corporation. He is a co-founder of BAC of VA, LLC, a small company that provides design support and castings for the military and specialty vehicle market. He is an SAE Fellow, Chairman Alabama Section of SAE, a past president of the Ductile Iron Society, former Vice-Chairman of the Governors Board of Transportation Safety for the Commonwealth of Virginia and a current member of AFS, ASM International and AIST.
Derya Dispinar graduated from Metallurgical and Materials Engineering Department, Istanbul University in 1996. He started working as a Research Assistant at the same department and gained an MSc degree in 1999. He earned a PhD in Metallurgy and Materials, University of Birmingham, UK in 2002 after which he returned to Istanbul University and worked as an Assistant Professor. He has worked as a researcher in SINTEF Materials and Chemistry, Casting Group in Trondheim, Norway between 2007 and 2010 while doing a Post-Doc at Norwegian University of Science and Technology (NTNU). Since October 2010, he has been working as a Senior Researcher in Aluminium Group at TUBITAK (The Scientific and Technological Research Centre of Turkey).
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Modeling

Session Chairs:
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The History of Casting Process Simulation

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Abstract

Not many developments in recent decades have changed the understanding of the metalcasting process as fundamentally as casting process simulation has. The main intention of this paper is to provide an easy to read and attractive overview for foundrymen addressing the development, current state, and future of casting process simulation.

Keywords: simulation, filling, solidification, modeling, autonomous optimization, thermo-physical properties, microstructure, heat treatment, stress, distortion

Introduction

The description of the metal casting process in a physical-mathematical model and its simulation in a computer demanded the quantification of process parameters and process steps as they impact the casting quality.

The idea of utilizing numerical models to predict the filling and solidification of castings came from physicists, mathematicians, and mechanical engineers. Today, casting process simulation is utilized to develop a technical knowledge database, as a management tool to provide training and education to foundry personnel, and to facilitate communications both within a corporation as well as with customers.

The History

The theoretical fundamentals of heat conduction in solid matter were developed by Jean Baptiste Joseph Fourier at the Ecole Polytechnique in Paris. His thesis, “The Analytical Theory of Heat”, received awards in 1822. It has provided the basis for all following calculations of heat conduction and transfer in solid materials. The French physicist and engineer Claude-Louis Navier, and the Irish mathematician and physicist George Gabriel Stokes, subsequently provided the basics of flow dynamics. The differential equations describing fluid flow are now known as the Navier-Stokes equations. The basic equations describing diffusion were developed by Adolf Fick, who worked during the 19th century at the University of Zurich and published them in 1855.

In the 1950s, Paschkis used analog computers to predict the movement of a solidification front in one or two dimensions. With the development of the first digital computers, Fursund was the first who used computers to solve casting process related problems (penetration of steel into mold sand), in 1962. Three years later, Hentzel and Keverian
published their ground-breaking work about two dimensional simulation of steel casting solidification. They utilized a program developed by General Electric to simulate heat transfer.

In 1968, Vestby developed a 2-D model to evaluate temperature distributions during welding, using, for the first time, the finite difference method. Two years later, V. de Lange Davies used Vestby’s program to simulate feeding distances in plate-like castings. P. N. Hansen published his thesis describing his work to predict hot tears in steel castings (Figure 1) in 1975. In the preparation of this thesis, a 3-D model was programmed for the first time.

Starting at the beginning of the 1980s, the research and development activities around the topic of casting process simulation increased substantially in multiple locations. In addition to the activities at the Technical University of Denmark around Hansen (Figure 2), work groups were established world-wide, including Berry and Pelke in the United States, Niyama in Japan, and Kurz in Lausanne, Durand in Grenoble and most notably, Sahm in Aachen at the Foundry Institute (Figure 3). Important milestones were the introduction of the term, “criteria function” by Hansen and Berry (1980), the introduction of a criteria function to depict centerline porosities by Niyama (1982), as well as the proposal of a criteria function to detect hot tears in steel castings by Flender and Hansen (1984). By the end of the 1980s, the first solutions to simulate the mold filling were provided.

In the 1990s, development activities focused on the simulation of stresses and distortions in castings (Hattel and Hansen, 1990), as well as the first steps were taken to predict microstructures and mechanical properties by Svensson and Wessen in Sweden.

Figure 1: The first results of a temperature distribution. (Hansen, 1975) Figure 2: Display of a low pressure die cast wheel. (Sahm and Hansen, 1984)

The Methods

Numerical simulation is the process of solving a physical model through mathematical (differential) equations and the display of the calculated domain (the casting and the mold) through discrete single elements. In order to calculate the differential equations, several methods were developed (FEM, FDM, FVM, BM, MM, etc.), which will not be discussed in detail here. In 1924, Schmidt developed a graphical method to solve 1-D heat conduction problems. In 1949 and 1959, important contributions regarding the analytical solution of heat transfer problems were provided by Ingersol, Zobel and Ingersoll, as well as by Carslaw and Jaeger.
The finite element method (FEM) was developed in 1945, to solve special load calculations. In 1956, the first structural simulations were conducted on airplane wings at Boeing. In 1967, the reference book, "The Finite Element Method", was published by Zienkiewicz. Hansen performed 2-D- and 3-D solidification calculations for the first time in 1975 utilizing the finite volume method (FVM). Each method has specific benefits and drawbacks and can yield good qualitative results depending on its area of application. The finite element methods have their roots in load simulations. The finite difference and finite volume methods come from the fluid flow simulation and show benefits in the description of heat and material transport phenomena.

The choice of which numerical method and mesh is used is driven by finding the best compromise between the quality (accuracy) of the calculation, optional automatic enmeshment and calculation time.

The first steps of describing the process in virtual terms were taken by focusing on heat transfer calculations and focused on the solidification process. The mold filling is an integral part of the process and therefore must be considered. This is not only important for the gating layout but for the detection of filling related defects as well. Indeed, the inhomogeneous temperature distribution in the melt caused by the filling process has in many cases an impact on the solidification process (Figure 4).

Even today, the dynamics of the mold filling process are often underestimated by practitioners. Key words like "quiescent filling" and "laminar flow" are frequently used, but from a physical point of view, all filling processes from sand castings to high pressure die castings are highly turbulent. This fact is based on the rheological properties of metal melts. The energy that is created by the flowing melt is so high that it cannot be eliminated through foundry technological efforts. Therefore, strong turbulences and eddy currents are found inside the melt even when the melt surface appears to be rising quietly (Figure 5). Many casting defects result from these under-surface movements, as well as reactions between melt and mold material. These defects include mold defects, air entrapments, oxidation defects, slag entrainments or metallurgical challenges (Figure 6).
As soon as a 3-dimensional geometry of a casting is available, a basic solidification and cooling simulation can be performed in minutes (Figure 7). The prediction of hot spots and areas of final solidification do not only help the metal caster in the engineering department, but also support the designer in evaluating the designs. The knowledge of temperatures and solidification behavior leads to a quantitative prediction of the local thermal Modulus in the casting, as well as solidification times, cooling rates, temperature gradients and shrinkage defects (Figure 8).
The Core Question in Engineering – Feeding and Shrinkage Defects

Prediction of feeding related problems is still one of the most important uses of casting simulation software. Depending on the alloy poured, different feeding behaviors and self-feeding capabilities need to be considered to provide a defect-free casting. Solidification simulation has to be combined with density and mass transport calculations in order to evaluate the impact of the solidification morphology on the feeding behavior, as well as to consider alloy dependent feeding ranges.

The Multitude of Materials

Even if the fundamental physics for filling, solidification, stress development, and cooling process are the same for all alloys, the specific material behavior makes a difference, as displayed in Figure 9 for aluminum alloys. As well as the process conditions, the nominal composition and metallurgical parameters (grain refinement) are defined. Based on this information, the program calculates the potential equilibrium phases, which are impacted by the accelerated cooling conditions they experience (phase kinetics). The inhomogeneous solubility of alloying elements in the solid and the liquid phase leads to segregations and thereby to the potential creation of new, and sometimes undesired, phases. Only in the final step, based on this information, the solidification progress and the resulting temperature distributions are calculated in a time step. These steps are repeated for every location and every point in time before microstructures and mechanical properties are predicted.

The key to the development of material-specific simulation models was the specific feeding behavior of cast alloys and their strong dependence on the chosen metallurgy. A calculation of the feeding behavior based solely on temperature distributions was not
sufficient. For example, large hotspots in iron castings can potentially completely feed themselves, but small hot spots can lead to shrinkage defects. The local shrinking and expansion behavior of a casting can only be calculated under the consideration of the locally developing phases (graphite, austenite, cementite) and their respective contribution to the local shrinking and expansion behavior. The nucleation and growth kinetics of each phase is therefore considered throughout the entire progression of the solidification. This means that for cast iron not only is the dominant impact of the alloying elements considered, but also the inoculation and melt quality. Metalcasters use the impact of the inoculation or alloying elements for the creation or avoidance of white iron. These are overlaid by the local cooling conditions inside a casting. A simulation solely of the macroscopic solidification and cooling behavior cannot describe this interaction. Therefore, this so-called micromodeling is performed on many materials, considering the amount of any new phase created at any time based on the phenomena described above (Figure 10).

Figure 9: Overview of input parameters, calculation steps, and results for the prediction of microstructures in aluminum alloys.

Figure 10: Differences between macroscopic and microscopic simulation (micromodeling) on simulated cooling curves.

Stresses and Distortion

The developments regarding the prediction of hot tears, as well as the creation of residual stresses and distortion behavior created much more transparency (Figure 11). Additionally, the stress simulation has to consider not only the part itself, but also the impact of mold and cores, as they are often predominantly responsible for stress-related defects (Figure 12).

In addition to residual stresses, hot tears, crack formation and the shrinkage and warpage of the castings, dies and permanent molds are moving into focus. Due to the high costs for permanent molds and dies, maintenance and repair efforts are very often the deciding factor if a process is profitable. As the temperature behavior and the resulting stress development can easily be simulated, this application of simulation provides additional value and cost reduction potential (Figure 13).