INVESTMENT CASTING INSTITUTE

64th Annual Technical Conference & Equipment Exposition

Covington, Kentucky

The Investment Casting Institute would like to thank the following companies who have sponsored the **64th Technical Conference & Equipment Exposition**

AluChem Booth 238
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Paramelt Booth 214
Westech Wax Products, Inc. Booth 421

The Investment Casting Institute would like to thank the following companies who have cast the awards for the **64th Technical Conference & Equipment Exposition**

ARISTO CAST
INVESTMENT CASTING

Artcast inc

Aristo-Cast, Inc.
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Georgetown, Ontario L7G 4R9
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fax (905) 877-0205
www.artcast.com

The Investment Casting Institute would like to thank the following Member companies for their educational support and promotion of the industry. Two scholarships are being offered in honor of the following individuals:

Larry Blum of Aristo-Cast

Hank and Laurie Harvey

The Investment Casting Institute would like to thank the following individuals who ran for the 2017 Board of Directors election.

Thank you to the following candidates listed below who have been nominated to fill the Regular Member openings on the Board of Directors:

John Marcin
Pratt & Whitney

Al Torok
Yamaha Marine Precision Propellers, Inc.

Thank you to the following candidates listed below who have been nominated to fill the Affiliate Member opening on the Board of Directors:

Michael Hascher
Eagle Engineered Solutions

Paul Novak
South Coast Mold, Inc.

The Investment Casting Institute would like to thank the following advertisers who have placed ads in INCAST Magazine and INCAST News for 2017.

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INVESTMENT CASTING INSTITUTE

MISSION STATEMENT

The Investment Casting Institute will market the investment casting industry and support its members by facilitating professional, academic, educational, and technical interests, and will provide a forum for advancement in technology and product quality for customers and manufacturers, while promoting free trade, fair competition, and adhering to U.S. laws and regulations regarding commerce and industrial trade.

GENERAL RULES OF ANTITRUST COMPLIANCE

The following rules are applicable to all ICI activities and must be observed in all situations and under all circumstances, without exception or qualification other than as noted below:

1. Neither the ICI nor any committee, conference or activity of the ICI shall be used for the purpose of bringing about, or attempting to bring about, any understanding or agreement, whether written or oral, formal or informal, expressed or implied, among competitors with regard to prices, terms or conditions of sale, discounts, tying provision or purchase of a good or service with another, exclusive dealing arrangements, distribution, volume of production, allocation of territories or customers, restrictions on non-deceptive advertising, or credit of suppliers, customers or competitors or any understanding or agreement which could be perceived as restraining competition.

2. No ICI activity or communication shall (a) include discussion, survey, or action, for any purpose or in any fashion of costs, prices or pricing methods, rebates or other price discrimination, production quotas or other limitations on either the timing or volume of production or of sales; (b) take any action likely to raise prices or reduce quantity or quality of goods available, or (c) involve allocation of territories or markets or customers in any way. “Communication” includes but is not limited to electronic communications, such as emails, test messages, faxes, blog or web posts and/or social media posts.

3. No ICI committee shall undertake any activity, which involves exchange or collection and dissemination among competitors, of any information regarding prices, pricing methods, costs of production, or of sales or distribution or individual company statistics of any kind, without first obtaining the advice of legal counsel, provided by ICI, as to those proper and lawful methods by which these activities may be pursued.

4. No ICI activity or communication shall include any discussion or action which may tend to or may be construed as an attempt to prevent any person or business entity from gaining access to any market or to any customer for goods or services, or to prevent or boycott any supplier, competitor, customer, or other entity from obtaining, accessing, or selling a supply of goods or otherwise purchasing or distributing goods or services freely in the market.

5. No ICI activity or communication shall include any discussion or action which might be construed as an agreement or understanding to refrain from purchasing any raw materials, equipment, services or other supplies from any supplier.

6. Neither ICI nor any committee thereof, shall make any effort to bring about the standardization of any product or method of manufacture, credentialing, listing or certification of any product or program for the purpose of preventing the manufacture or sale of any product not conforming to a specified standard or which would tend to have the overall affect of either lessening competition or resulting in a degree of price stabilization.

7. No person or company shall be commercially disparaged nor shall any ICI Member make statements that are reasonably likely to have a negative reputational impact on another so as to exclude that person or company from ICI membership or participation in any ICI activity where such exclusion is designed to or may impair such person's or company's ability to compete effectively in the investment casting industry.

8. In conducting ICI committee meetings, the chairman thereof shall prepare and follow a formal agenda which shall be provided to all committee members prior to the meeting; else it shall not be considered. Agenda items listed as “Any Other Business: shall be prohibited. Minutes of each meeting shall be distributed to all persons who attended such meetings. Approval of the minutes shall be obtained from the membership of the committee at its next meeting. Copies of the minutes shall be transmitted to the headquarters staff.

9. ICI speakers and authors of conference papers shall be informed of the need to comply with ICI's antitrust policy in the preparation and presentation of their papers and addresses.

10. In informal or social discussions at the site of an ICI meeting (whether such meetings are conducted in-person or via telecommunications services), which are beyond the control of its officers and chairmen, all representatives are expected to observe the same standards of personal conduct required of ICI in its compliance with these antitrust guidelines. Members are reminded that even actions or discussions occurring outside of the U.S. may still be subject to federal antitrust laws. In addition, copies of the foregoing Antitrust Policy Statement and General Rules of Antitrust Compliance will be included in registration packets and will also be printed in the ICI Committee Directory. The Board may from time to time require all members to sign an acknowledgement that each member has read and understood these Rules of Antitrust Compliance.

ANTITRUST POLICY STATEMENT OF THE INVESTMENT CASTING INSTITUTE

The Investment Casting Institute (ICI) is a trade and technical association of investment casting foundries (and their suppliers) where castings of metal are made.

The ICI is organized to promote the common interests of the investment casting industry. The ICI is not intended to become, and will not become, involved in the competitive business decisions of its members, nor will it take any action which would tend to restrain competition in the investment casting industry.

Nevertheless, it is recognized by the Board of Directors of ICI that the Institute itself, as well as its varied activities, could be regarded by some as a forum or opportunity to promote anti-competitive conduct. For this reason, the Board of Directors promulgates this statement of policy to make clear its unequivocal support for the policy of competition served by federal and state antitrust laws, as well as its uncompromising intent to comply strictly in all respects with those laws.

In addition to stating the ICI's firm commitment to the principle of competition served by antitrust laws, the ICI also wishes to advise that the penalties which may be imposed upon both ICI and its individual and corporate members involved in any violation of such laws are now so severe that prudent business judgment demands that every effort be made to avoid any such violation. In addition to injunctions and other equitable remedies, violations of the Sherman Act, such as price-fixing, are felony crimes for which individuals may now be imprisoned for up to ten (10) years and fined up to one million dollars ($1,000,000.00), and corporations can be fined up to 100 million dollars ($100,000,000.00) for each offense, or twenty percent (20%) of affected commerce. The Department of Justice has recently obtained fines of up to five hundred million dollars ($500,000,000.00). Under the Sherman Act, state Anti Trust law, the Federal Trade Commission Act and Robinson-Patman Act, treble (triple) damage claims based on the amount of gain or loss by private parties (including class actions) for antitrust violations are extremely expensive to litigate and can result in judgments of a magnitude which could destroy the ICI and seriously affect the financial interests of its members. This includes attorney’s fees and “joint and several liability” where one may be liable for an entire Judgement even though their role in the antitrust violation was rather small.

It is the responsibility of every member of the ICI to be guided by ICI's policy of strict compliance with antitrust laws in all ICI activities. It shall be the special responsibility of ICI officers, directors and committee chairmen to ensure that this policy is known and adhered to in the course of activities pursued under their leadership.

To assist the ICI staff and all its officers, directors and committee chairmen in recognizing situations which may raise the appearance of an antitrust problem, the Board will as a matter of policy furnish to each of such persons copies of ICI's General Rules of Antitrust Compliance. The ICI will also make available general legal advice when questions arise as to the manner in which the antitrust laws may apply to the activities of the ICI or to any committee thereof.

Antitrust compliance is the responsibility of every ICI member. If you have any questions or information concerning potentially anti-competitive conduct, please contact the Board’s Executive Committee orally, in writing and even anonymously. Alleged violations of the ICI General Rules of Antitrust Compliance or of this policy statement will be vigorously investigated and reviewed with due process pursuant to the by-laws of the ICI; violations may result in revocation of membership in ICI and removal from any ICI office.

64th Annual Technical Conference & Equipment Exposition

AGENDA

Receptions
SUNDAY 6:00 P.M.
TUESDAY 6:30 P.M.

Equipment Expo
MONDAY 2:00 P.M. - 6:00 P.M.
TUESDAY 2:00 P.M. - 6:00 P.M.

SUNDAY, OCTOBER 15, 2017

3:00 p.m. - 6:00 p.m.	**REGISTRATION**
6:00 p.m. - 7:30 p.m.	**WELCOME RECEPTION**

MONDAY, OCTOBER 16, 2017

8:00 a.m. - 8:10 a.m.	**WELCOME INTRODUCTION**
8:10 a.m. - 8:40 a.m.	**2017 Casting Contest, Innovator of the Year, Hall of Honor and Honorary Member Awards** **Tim Sullivan, Esq.** ***Hitchiner Manufacturing, ICI Director, Awards Committee Chairman***
8:40 a.m. - 9:10 a.m.	**2017 INTERN SCHOLARSHIP AWARDS** **Russ Rosmait, Ph.D.,** ***Pittsburg State University, ICI Academic Advisor***
9:10 a.m. - 10:10 a.m.	**KEYNOTE ADDRESS:** ***Planning Is Important But Improvising is Essential*** **Avish Parashar**
10:10 a.m. - 10:30 a.m.	**Coffee Break sponsored by Paramelt**
10:30 a.m. - 10:50 a.m.	How will 3D Metal Printing Impact Investment Casting? **Tom Mueller,** ***Mueller Additive Manufacturing Solutions***
10:50 a.m. - 11:10 a.m.	Advancing Sculpture **Rob Arps,** **Eyal Chernichovsky,** ***Form 3D Foundry***
11:10 a.m. - 11:30 a.m.	3D Printed Ceramic Cores and Shells for Investment Casting Through Large Area Maskless Photopolymerization (LAMP) Technology **Dr. Suman Das,** ***DDM Systems***

MONDAY, continued

11:30 p.m. - 12:00 p.m.	Additive Manufacturing/ 3D Printing Discussion Panel **John Marcin,** ***Pratt & Whitney, ICI Director***
12:00 p.m. - 1:00 p.m.	**LUNCH**
1:00 p.m. - 1:30 p.m.	Industry 4.0 for Investment Casting **Michael Kügelgen,** ***MK Technology GmbH***
1:30 p.m. - 2:00 p.m.	Prototyping Opportunities for Investment Castings, From an Ounce to 9,000 lb. **Will Jeffs, James Collins** ***Castings Technology International***
2:00 p.m. - 6:00 p.m.	**EXPO**

TUESDAY, OCTOBER 17, 2017

8:00 a.m. - 8:10 a.m.	**OPENING REMARKS**
8:10 a.m. - 8:55 a.m.	Permeability Panel Discussion **Julie Markee,** ***Key Process Innovations, ICI Director,*** **Nipendra "Nip" Singh,** ***S&A Consulting, ICI Director*** **Craig Lanham, Taylor Thornhill, O'Fallon Casting**
8:55 a.m. - 9:25 a.m.	Comprehensive Study of Thermo-Physical Properties of Investment Shells **Mingzhi Xu,** ***Missouri University of Science and Technology***
9:25 a.m. - 10:10 a.m.	Economical Engineered Powder Blends for Precision Investment Casting Backup Slurries- "How Its Made" **Scot Graddick,** ***Imerys Refractory Minerals***

TUESDAY, continued

10:10 a.m. - 10:30 a.m.	**Coffee Break sponsored by AluChem**
10:30 a.m. - 11:00 a.m.	Optimizing the Tetrashell Build Structure to Reduce Shell Cracking in the Autoclave with SLA Patterns **Kevin Zaras, *DSM SOMOS***
11:00 a.m. - 11:30 a.m.	Improved Consistency of Slurry and Shell Properties using Particle Size Control of Ceramic Flours **Tom Branscomb, *Buntrock Industries***
11:30 a.m. - 12:00 p.m.	Autonomous Engineering Applied to Investment Casting Processes **Gerald Richard,** ***Magma Foundry Technologies***
12:00 p.m. - 1:00 p.m.	**LUNCH**
1:00 p.m. - 1:30 p.m.	Process Control Standards Update **Nipendra “Nip” Singh,** ***S&A Consulting, ICI Director***
1:30 p.m. - 2:00 p.m.	Update on ICI-AFS Joint Research Project on MMPDS Inclusion of 17-4 PH and 15-5 PH Investment Cast Steels **Jiten Shah,** ***Product Development & Analysis (PDA)*** **Al Torok, *ICI Director,*** ***Yamaha Marine Precision Propellers*** **Dr. Zayna Connor, *AFS, Inc.***
2:00 p.m. - 6:00 p.m.	**EXPO**
6:30 p.m. - 8:00 p.m.	**RECEPTION**

WEDNESDAY, OCTOBER 18, 2017

8:00 a.m. - 8:10 a.m.	**OPENING REMARKS**
8:10 a.m. - 8:35 a.m.	Case Study: Recruitment and Retention Challenges of Today and Beyond **Tim Sullivan, Esq.** ***Hitchiner Manufacturing, ICI Director,*** ***Awards Committee Chairman***
8:35 a.m. - 9:00 a.m.	Case Study: The Merging of Cultures in an Acquisition: Personnel, Systems and Technology **Cliff Fischer,** ***Wisconsin Precision Casting, ICI Director***
9:00 a.m. - 9:25 a.m.	Case Study: Plant Modernization: Navigating Challenges and Overcoming Obstacles **Vince Gimeno, *O'Fallon Casting***

WEDNESDAY, continued

9:25 a.m. - 10:00 a.m.	Managing Change Discussion Panel **Brad DeSplinter,** ***TPM Inc., ICI Director***
10:00 a.m. - 10:20 a.m.	**Coffee Break**
10:20 a.m. - 10:50 a.m.	Fluid Flow Modeling Validation of Complex Geometries **Alan Druschitz, *Virginia Tech***
10:50 a.m. - 11:20 a.m.	An Introduction to Self-Monitoring, Adaptive Recalculating Treatment Technology (SMARTT) in Degassing Aluminum **Brian Began, *Foseco***
11:20 a.m. - 11:50 a.m.	Using Computer Simulation to Drive the Design of Feeding Systems for Investment Castings **David Schmidt,** ***Finite Solutions, Inc.***

SPEAKERS

Avish Parashar **Keynote Speaker**
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Eyal Chernichovsky **Paper No: 2**
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James Collins **Paper No: 5**
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Nip Singh **Permeability Panel Discussion**
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Craig Lanham **Permeability Panel Discussion**
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Taylor Thornhill **Permeability Panel Discussion**
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SPEAKER BIOGRAPHIES

Avish Parashar .... Keynote Address
Motivational Speaker – Avish Parashar Productions, Inc.
Avish graduated from the University of Pennsylvania in 1995, and worked in IT for seven years. While working “normal” jobs, he created, managed, and directed Polywumpus Improv Comedy from 1996-2002, and then performed, taught, and directed improv with Full Circle Theater from 2002 to 2008. In 2003 Avish launched his speaking and training business, Combining his experience in improv comedy and his experience working in a variety of environments, Including a Fortune 500 company (Chase Manhattan), a small family-run business, and an Internet startup. Avish created a unique, entertaining, and relevant approach to speaking and training. Avish Parashar is a funny motivational keynote speaker whose programs are a unique blend of humor, content, and interaction that makes the information relevant, engaging, and memorable. As a motivational keynote speaker, Avish energizes, inspires, and entertains his audiences while giving them the tools to respond to critical challenges.

Tom Mueller .... Paper No: 1
President – Mueller Additive Manufacturing Solutions
Tom is the founder and president of Mueller Additive Manufacturing Solutions, a consulting company focusing on metal casting applications of additive manufacturing. He has been involved in 3D printing applications for more than 25 years. He led the first beta site for stereolithography at Baxter Healthcare in the late 80s. He then went on to found two 3D printing service companies. One of those companies, Express Pattern, was sold to 3D Systems. He worked for 3D Systems as Director of Business Development focusing on metal casting applications and later for Voxeljet as Director of Metal Casting applications. He currently is a consultant on metal casting applications of additive manufacturing. Tom has published more than 50 technical papers and journal articles related to 3D printing applications. He holds BSME and MSME degrees from the University of Illinois and an MBA from the Sloan School of Management at MIT.

Rob Arps .... Paper No: 2
Founder – Form 3D Foundry
Rob Arps is Founder and CEO of Form 3D Foundry. With over twenty years of classical artistry in traditional sculpting methods under his belt and fascination of science and technology, Rob’s natural progression in 2000 integrated engineering tools and software from the automotive and aerospace industry into his art practice. This began improvements in cost and time without sacrificing quality. The results of increasing productivity and profitability, without compromising quality were immediate. Ultimately, technology created a sea change of radical improvements, unheard-of possibilities, and limitless potential. More importantly, Rob’s unique and innovative use of technology has afforded him the opportunity to collaborate with some of the most creative and successful artists, architects, and design houses in the country.

Eyal Chernichovsky .... Paper No: 2
Design Process Engineer & Production Program Manager – Form 3D Foundry
As Form 3D Foundry Design Process Engineer and Production Program Manager, Eyal Chernichovsky is recognized for an inventive problem solving aptitude alongside analytical skills. Eyal finds that the simplest and most cost effective solutions in production and fabrication situations are the ones that he takes most satisfaction in because of the fundamentals they take to attain; a process geared towards a totality in additive manufacturing, computational design, a 3D dimensional brain (sometimes 4D), a deep understanding of the medium at hand and passion for art, design and engineering as one.

Dr. Suman Das .... Paper No: 3
Co-Founder – DDM Systems
Suman Das is a co-founder of DDM Systems, an Atlanta-based additive manufacturing company commercializing LAMP and SLE technologies for 3D printing of ceramics and metals. Das received his Ph.D. in mechanical engineering from The University of Texas at Austin. He is a professor of mechanical engineering at Georgia Tech and has over 25 years of experience in 3D printing and additive manufacturing. His work on additive techniques spans metals, polymers, ceramics and composites using lasers and UV light sources.

SPEAKER BIOGRAPHIES

Michael Kugelgen..……...……………………………………………………………………………..……….Paper No: 4

General Manager – MK Technology GmbH

Michael Kügelgen, General Manager of MK Technology GmbH, worked from 1987 in the company "International Aerospace Technologies" as the leader of the development and production for Unmanned Air-Vehicles, UAV's. In 1993 he started with his own Engineering Office Kügelgen & Partner in Bonn. His major activities were construction and consulting services in the aviation sector, as well as general construction services worldwide. In early 1997 after the implantation of a feasibility study in the field of Rapid Prototyping / Rapid Tooling Michael Kügelgen decided to build up beside the consultant work his own production to develop appropriate machines. Meanwhile, MK Technology GmbH is a modern production facility and has its own training centre. Apart from the standard programme customized systems are also available. Michael Kügelgen with his company MK Technology GmbH has won twelve innovation prices and awards in the field of Rapid Prototyping and holds several patents.

Will Jeffs…..,………………………………………………………………………………………………….…Paper No: 5

Technical Development Manager – Castings Technology International

During over 30 years at Cti, Will has become renowned globally for his practical knowledge and experience in all aspects of high alloy manufacture and the application of ceramic moulding processes for both conventional and reactive alloys in a wide range of manufacturing facilities. Will was educated in the original "steel city" of Sheffield at the Hallam University, where he studied "extractive Metallurgy" and has hands on operating experience of all elements of casting manufacture, in addition to managing Cti's in-house casting operations for many years and was a key member of th team that developed the Replicast® process. In his current role, Will is responsible for promoting licenses for all Cti technologies, transferring relevant know-how and providing ongoing support. Exposure to Rapid-prototyping techniques and opportunities from the hand cut foam and charred phone directories of last century, right through to the latest printed parts has given a unique insight to this field of small batch manufacture, particularly at the larger end of the market.

James Collins……...…………………..………………………………………………….……………………Paper No: 5

Foundry Process Consultant – Castings Technology International

James joined Cti after roles working in the steel industry and production of high value metals. His academic grounding was in engineering materials, achieved with honours at The University of Sheffield. James works closely with member foundries, applying his hands on experience in all of Cti's process technologies. James has direct experience in air/vacuum melting, mould manufacture, ceramics processing, pattern manufacture and a range of post cast processes. In his current role, he has worked on the implementation of numerous technologies around the world, as well supporting activities in-house at Cti, both for member based projects and developing know-how. James continues to work on most major projects, being intrinsically involved in process/equipment commissioning, training, process development and support, in most casting disciplines.

Julie Markee…..…………………………………………………………………………..Permeability Panel Discussion

Managing Director – Key Process Innovations

Julie Markee is a highly conscientious, detail-oriented Process Engineer who has built an excellent reputation for technical expertise in the Precision Investment Casting Industry. She has extensive experience and proven ability for defect analysis, process improvement and operator training systems across a wide range of foundries including commercial, aerospace and titanium. She has presented numerous technical papers focused on helping PIC foundries remove variability from their process. She is also serving as a member of the Investment Casting Institute's Board of Directors, is the chair of the Publications Committee and is currently working with an Education subcommittee to update the ICI Process Control Class.

Nipendra (Nip) Singh…..……………..……………………………………………………Permeability Panel Discussion

Consulting Partner & CEO – S&A Consulting Group LLP

Nipendra (Nip) Singh has almost 40 years of experience in the high technology aircraft engine components manufacturing business including nearly 20 years with Rolls Royce , General Electric and TRW/PCC Corporations. Early in his career Mr. Singh managed the design and startup of a new investment casting plant for General Electric Company. Since 1991 Nip is Consulting Partner and CEO of S&A Consulting Group LLP, Cleveland, USA. He was educated in India having received a degree in Metallurgy and did post graduate work in business at Case Western Reserve University. His background includes marketing strategies, product engineering, strategic management and new plant construction in aerospace and commercial ventures. He has consulted for over 24 years for multi-national and American companies in the US, Japan, Europe and Asia. Nip has been an affiliate member of ICI for more than 20 years. He is also ICI member of Board of Directors, working/chairing many key committees for the welfare of Investment Casting in general and both Affiliate and Regular members.

SPEAKER BIOGRAPHIES

Craig Lanham…………………………………………………………………………..…Permeability Panel Discussion
Retired - Ceradyne, Inc. - A 3M Company
Mr. Craig Lanham, recently retired from Ceradyne Inc., a 3M Company, received his BS Degree from Carroll College, Waukesha, Wisconsin in 1971. During his career Mr. Lanham spent over 44 years involved in the manufacturing of casting with 38 years of that experience in the Precision Investment Casting Industry. His experience included a healthy balance between direct investment casting manufacturing experience and management responsibilities at two investment casting foundries; Northern Precision Castings and Kovatch Castings and experience in the marketing and sales of consumables to Investment Casting Foundries; first with REMET and then Minco / Ceradyne. Over his many years in the industry Mr. Lanham has maintained a long standing and active association with the Investment Casting Institute. In this relationship he was a committee member in the writing of their current WAX GUIDE publication, an instructor for 5 years to the Process Control Course and an author of several technical papers.

Taylor Thornhill...Permeability Panel Discussion
Process Engineer – O'Fallon Casting
Taylor graduated from Missouri University of Science and Technology in 2015 with a degree in Metallurgical Engineering. While attending university, he obtained internships with O'Fallon Casting in O'Fallon, MO, and Alcoa Howmet in Whitehall, MI. The Investment Casting Institute awarded him with the National Intern Scholarship in 2014, and 2015 for these experiences. Taylor is currently work for O'Fallon Casting as part of their Process Engineering team. There, he has continued in his pioneering effort towards smarter materials and better technology, so we can all advance faster, safer, and cleaner.

Thad Nykiel ....Permeability Panel Discussion
Process Engineering Manager – Bescast, Inc.
Thad Nykiel has been in the investment casting industry for over 38 years. Shortly after graduating from Cleveland State with a BS in Metallurgical Engineering, he started working in the precision investment casting industry. Some of the foundries Thad has worked at include PMI, PCC and most recently Bescast where he has been working for a little over 15 years. Thad is passionate about the industry and finds the diversity of process challenges allows him to continue to expand his knowledge of the process and the industry as a whole.

Dr. Mingzhi Xu.. Paper No: 6
Assistant Research Professor – Missouri University Science & Technology
Dr. Mingzhi Xu is an assistant research professor at Missouri University of Science and Technology. He received his Ph.D in Metallurgical engineering in 2015 at Missouri University of Science and Technology under Dr. Von Richards' advisory. He has been dedicated on investment shell related research for more then seven years. He developed an algorithm to measure the thermal properties of porous investment shell under equilibrium condition using laser flash technique. He also generated in-situ thermal properties database for various investment shells and those database have been widely used in commercial simulation software and investment shops. He has more than ten publications that are related to investment shell research.

Scot Graddick .... Paper No: 7
Technical Director – Imerys Refractory Minerals
Scot Graddick is the Technical Director for Imerys Refractory Minerals-North America, as well as the Product Manager for Imerys' Mulcoa aluminosilicate and TECO-Sil fused silica product lines. Scot is a 1985 graduate of Furman University in Greenville, South Carolina, where he received a BS degree in Geology (with focus on mineralogy/geochemistry). He was originally employed by Allied Mineral Products, Columbus, OH, where he worked for four years as a Research Mineralogist/Monolithic Refractories Development. Imerys hired Scot in 1991, and he has worked in several capacities for Imerys since that time. These include: VP of Operations/C-E Minerals TECO plant (Greeneville, Tennessee), VP of Operations/C-E Minerals Mulcoa plant (Andersonville, Georgia), and VP of Research and Technology/C-E Minerals (Roswell, Georgia). Scot has worked very closely with Imerys' investment casting sales distribution network through the years, as well as in direct sales to the investment casting and refractories industries, all over the world.

SPEAKER BIOGRAPHIES

Kevin Zaras……………………………………………………………………………………………………..Paper No: 8
Application Development Manager – DSM Somos
Kevin Zaras holds bachelor's degrees in Microbiology and Chemistry from Western Illinois University and Roosevelt University respectively. Kevin's main expertise lies within the 3D Printing/Additive Manufacturing industry where he has over 12 years of experience having held positions as R&D Chemist, Product Manager, Sales Account Manager and currently is Application Development Manager for DSM Somos' line of SLA resins. In this role, he helps customers find innovative ways to adopt additive technologies into their production and manufacturing processes.

Tom Branscomb .... Paper No: 9
Technical Director – Buntrock Industries, Inc.
Mr. Branscomb is the Technical Director for Buntrock Industries, Inc. He graduated in 1970 with a Master of Science degree in Ceramic Engineering from Iowa State University. After 4 years in the refractories industry in research and special projects, he joined Precision Castparts Corp. in Portland, Oregon where he spent 25 years holding various positions including: senior ceramic research engineer, foundry process engineer, shell room manager, process control manager, and process engineering manager. Tom joined Buntrock Industries in 1999. He operates a customer service and research lab in Portland and is very active in shell development. Tom served one 3 year term on the ICI Board of Directors in 2002 - 2004 as an Affiliate Member.

Gerald Richard………………………………………………………………………………………………..Paper No: 10
Application Manager – MAGMA Foundry Technologies, Inc.
Gerald Richard is an Application Manager at MAGMA Foundry Technologies Inc., a software company that is committed to casting excellence and achieves this through its casting process simulation tool MAGMASOFT®. Before devoting his life to the foundry industry, Gerald achieved a BS degree in Mechanical Engineering from Marquette University. He went on to work in the chemical industry as an engineer for 5 years before pursuing an opportunity to work at Badger Alloys, a high alloy jobbing foundry locate in Milwaukee, WI. Gerald fell in love with castings and the casting process as he worked as a foundry engineer focusing mostly on gating and risering design. After 4 years of working at Badger Alloys, Gerald moved to the greater Chicago area and began working for MAGMA Foundry Technologies Inc. in 2015, where he focuses on client development and support.

Jiten Shah……....……………………………………………………………………......ICI / AFS Joint Research Project
Founder & President – Product Development & Analysis (PDA) LLC.
Mr. Jiten Shah is the Founder and President of Product Development & Analysis (PDA) LLC located in Naperville since 1993 and brings over 30 years of experience in the design of casting, rigging and process; manufacturing solutions and contract research utilizing state of the art virtual simulation tools such as CAD, FEA, CFD, 3D scanning, Casting Process Simulation, rapid prototyping and additive manufacturing. Mr. Shah has been a PI and/or managed contract research programs for various agencies including DARPA, ARDEC, DOD-RDECOM, DOE, DLA, NASA and is a member with active projects with three Manufacturing innovation Institutes - DMDII (Digital Manufacturing Design Innovation Institute), LIFT (Lightweight Innovations for tomorrow) and America Makes. Prior to founding PDA LLC, Mr. Shah worked for Rockwell International - Off-Highway division (now Bradken-Atchison Steel Foundry), Foseco and a few foundries in India. Mr. Shah has Masters in Foundry Technology from Indian Institute of Technology - Kharagpur; attended graduate program at the University of Southern California and has MS in Mechanical & Aerospace from Illinois Institute of Technology, Chicago.

Al Torok .... ICI / AFS Joint Research Project
IC Technical Manager – Yamaha Marine Precision Propellers, Inc.
Al is currently the Investment Casting Technical Manager at Yamaha Marine Precision Propellers, Inc. located in Indianapolis, IN. After receiving his BS in Physics at St. Joseph's College in Rensselear, IN. Al has spent the last 41 years in the foundry Industry. Al started his investment career at Arwood, in New Hampshire in 1986. He has held various positions within the technical side of the foundry business, from starting out as a Lab Tech, to Director of Engineering at an aerospace foundry in Southern CA, to the present, as the Investment Casting Technical Manager at YMPPI. Al has technical engineering experience with casting large Aluminum, mid-size and small Low Carbon Steel, Alloy Steel and Stainless Steels, Copper base alloys, Magnesium alloys, Gray and Ductile Iron in both Shell and Solid Mold, for the aerospace industry. He further has engineering experience in Green Sand, Dry Sand, High Pressure Die Casting, Permanent Mold, Tilt Mold, Low Pressure. Al has co-authored five technical papers and has served on various technical committees for ASTM, ICI, Gray Iron, Ductile Iron and AFS research projects.

SPEAKER BIOGRAPHIES

Zayna Connor……………………………………………………………………………….. ICI / AFS Joint Research Project
Consultant – American Foundry Society
Zayna Connor is VP of Technical Services, American Foundry Society, where she currently oversees the technical department, including member technical support, technical committee activities and research projects. She is active in American Society of Materials, Past Chair of the Technical Books Committee. Zayna received her BS in Metallurgical Engineering from Missouri S&T and her PhD in Materials Science & Engineering from Northwestern University. Her dissertation on the quantitative analysis of fatigue cracks in riveted joints using scanning acoustic microscopy was under the direction of Prof. Morris Fine. She is a National Science Foundation Fellow and an Amelia Earhart fellow. Zayna has spent more than 30 years working in materials, castings, forgings extrusions and rolled products. She has helped develop casting suppliers in China, Poland, Turkey, Italy, US, Mexico and Canada. She was the R&D manager for non-heat treat alloys at Alcan Rolled Products.

Tim Sullivan……….………………………………………………...………………Managing Change Discussion Panel
Vice President of Administration – Hitchiner Manufacturing Co., Inc.
Graduated from Tufts University with a B.S. in biology and earned a Juris Doctorate from Suffolk University Law School and a certificate in strategic human resource management from Harvard University Graduate School of Business Administration. Employed by United Parcel Service 1986 to 1995 as corporate legal counsel (Atlanta, GA) and in various human resource functions at the district level (Maine, New Hampshire, and Massachusetts). Appointed to the State of New Hampshire Compensation Appeals Board by Governor Stephen Merrill in 1996. Joined Hitchiner as corporate manager of administration in 1995 with responsibilities ranging from managing in-house legal and administrative affairs to specific responsibilities in human resources including ethics compliance and training, corporate safety, and environmental affairs. Promoted to director of administration and corporate counsel for legal and administrative affairs. Appointed vice president, Administration in August 2005.

Cliff Fischer…...…………………………………………………….………………....Managing Change Discussion Panel
VP Manufacturing / Co-Owner – Wisconsin Precision Casting Corp.
Cliff graduated from Marquette University with a B.S. in Mechanical Engineering. He has worked in the manufacturing arena for 30+ years and 28 of those years in Investment Casting Industry. He currently is the Vice President and co-owner of Wisconsin Precision Casting Corp. Prior to Wisconsin Precision Casting, he worked at Signicast Corporation as a project engineer, plant manager and vice president of manufacturing. Cliff also has been a board member, Vice President and President of the Investment Casting Institute's board of directors and has served on many of the Institutes committees.

Vince Gimeno……………………………………………………………………..…….Managing Change Discussion Panel
General Manager – O'Fallon Casting
Vince Gimeno is the Chief Executive Officer/ General Manager of O'Fallon Casting. He joined the company in 2003 as part of the acquisition team of Hitchiner Manufacturing Company Nonferrous Division. O'Fallon Casting is a world leader in the production of nonferrous investment castings in a wide range of Aluminum, Copper-Based and Silicon Carbide Metal Matrix Composite Alloys. O'Fallon Casting also offers added value by furnishing castings machined and finished to the customer specifications. Rapid prototyping and concurring engineering accelerate the proof of concept to market. Servicing the aerospace, military and commercial industries with the latest technology available like digital radiography, compression straightening, digital production definition using laser scanning metrology are some of the tools used for customer satisfaction. At O'Fallon Casting Vince has achieved a dramatic transformation of the company. Reshaping the company's technical capabilities, continuous improvement events and implementing a new sophisticated computer system, resulting in an increase of revenue and doubling of market share. Before O'Fallon Casting, Mr. Vince Gimeno had a 28-year career with Alcoa Howmet Cercast / Cercor, a global leader in the production of nonferrous investment castings. At Cercor, Georgetown, Canada. Vince was appointed Plant Manager in 1995. He was responsible for the overall management, direction and coordination of the operation. He set the strategic plant goals and implemented plans to achieve them. He was instrumental in ensuring a sound fiscal operation, quality assurance and regulatory compliance. He was promoted as Quality Manager in 1980 at Cercor, Georgetown, Canada. Mr. Vince Gimeno implemented the ISO accreditation program. He achieved certification as Level III for nondestructive testing methods, liquid penetrant and radiography. Vince began as Quality Control Inspector in 1973 at Cercast, Montreal, Canada. He progressively gained specialized experience in the investment casting process. Vince was educated at Vanier College, in Montreal, Canada. He holds a degree in mechanical systems. He also is fluent in English, French and Spanish.

SPEAKER BIOGRAPHIES

Alan Druschitz…………………....……………….………………………………………….…………….….Paper No: 11
Associate Professor – Virginia Tech
Alan Druschitz joined the Virginia Tech College of Engineering in January of 2011 as an Associate Professor and the Director of VT-FIRE (Foundry Institute for Research and Education). He has 35 years of industrial materials research, product development, manufacturing support, management and teaching experience. His expertise includes automotive components, product design, failure analysis, melting, casting, heat-treating, welding, materials and component testing, and nondestructive testing. His research interests include structure-processing-properties relationships, casting process development, corrosion and additive manufacturing. A graduate of the Illinois Institute of Technology where he received his bachelor's degree in 1978 and his doctorate in 1982, both in metallurgical engineering, he started his professional career with General Motors Corporation. He left GM in 1996 to join the Intermet Corporation as the Director of Materials R&D. In 2007, he joined the University of Alabama at Birmingham. He has over 83 publications and six patents. He is a Fellow of the Society of Automotive Engineers and the Chair of the ASM International Handbook Committee. He is a member of the American Foundry Society, ASM International, TMS, Association for Iron and Steel Technology, and NACE International.

Brian Began………………………………………………………………………………………………...Paper No: 12
Product Manager – Foseco
Brian Began is a Product Manager, Non-Ferrous Metal Treatment at Foseco. Brian started with Foseco in February 1998 and has worked in a variety of roles. Brian Began graduated from Case Western Reserve University (CWRU) with a bachelor's degree in Materials Science and Engineering. His experiences within the foundry industry include CWRU's experimental foundry and cooperative education assignments at both Ford Motor Company's Cleveland Casting Plant and Element Materials Technology (formerly Climax Research Services) in Wixom, MI. Brian completed his Masters in Business Administration in April 2007 and an additional specialization in Finance in August 2007 from the Graduate School at Ashland University. Brian is the current Chairman for the AFS Aluminum Division Committee and has held numerous roles within both the Aluminum Division and the CAC-Ohio AFS chapter structure since 2001. Brian was the recipient of the 2011 AFS Glenn Stahl Service Award for service to the aluminum industry. Brian is a contributor of the permanent mold chapter within the forthcoming *Aluminum Casting Technology Book,* published by the AFS, and has published in both *Modern Castings* and *AFS Transactions*. Brian has also presented on various topics at AFS & NADCA chapter meetings, casting congresses and specialty conferences.

David C. Schmidt………..……………………………………………………….…………………………...Paper No: 13
Vice President – Finite Solutions, Inc.
Dave began his foundry career in 1980, when he worked with Professor Heine at the University of Wisconsin to develop a tapered risering technique for ductile iron castings. As a part of his degree work, Dave developed a computer program for riser size calculations, which ran on an Apple II computer. In 1983, Dave joined the American Foundrymen's Society, and started the AFSoftware Service, which developed computer applications for foundries. In 1985 AFS began marketing AFSolid, the world's first commercial casting simulation tool. In 1995, Dave joined Finite Solutions Inc as Vice President, and since then has spent his time in development, sales and support of casting simulation tools. He has authored more than 40 technical publications, focusing primarily on gating/riser design and casting simulation.

INVESTMENT CASTING INSTITUTE

How Will 3D Metal Printing Impact Investment Casting?

Tom Mueller
Mueller Additive Manufacturing Solutions

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 1

How will 3D Metal Printing Impact Investment Casting?

Tom Mueller, Mueller Additive Manufacturing Solutions

Background

Metal Additive Manufacturing, or 3D metal printing, has received a lot of attention in the last couple years. GE spent more than a billion dollars to purchase Arcam and Concept Laser and formed a new division called GE Additive. They predict they will have manufactured more than 100,000 metal components for their own use by 2020 and will be generating more than a billion dollars in AM revenues by that same year. Furthermore, they predict they will sell 10,000 metal printers in the next decade.

Desktop Metal, a startup formed by MIT professors, has received $115 million in funding from such corporations as Caterpillar, BMW and Lowes.

IDTechEx, a marketing research firm has predicted that the metal AM market will reach $6.6 billion by 2026, about the same size as the US investment casting market. 3Diligent, a metal printing service provider, claims that metal 3D printing will shape the Aerospace industry.

With press like this, it is no wonder that investment foundries are concerned about the potential loss of business to metal printing. Is metal printing likely to make investment casting obsolete?

This study was undertaken to examine that question.

Methodology

There are a number of reasons that one manufacturing method is chosen over another to create a metal component. Manufacturers may choose the method that provides the components in the shortest period of time, the method that provides the best metallurgical properties, or the method that provides the best surface finish. Most often, however, manufacturers will choose the least expensive method that provides acceptable quality. The objective of the study was to find those situations where metal printing might be less expensive than investment casting.

Of course the least expensive method in one situation may not be the least expensive in another. The potential scenarios in investment casting are many. Scenarios vary with part size, part complexity and production volumes. To cover the majority of the investment casting landscape, 75 different scenarios were defined consisting of 3 different part sizes, 5 different part complexities and 5 production volumes.

Part sizes chosen were 4 inches, 8 inches and 16 inches. Clearly investment casting is used to manufacture components both larger and smaller than this range, but this will cover the majority of the market.

Geometric complexities ranged from very simple to so complex they cannot likely be cast. Geometry 1 is a simple dome illustrated in Figure 1. The pattern could be created in a simple two part mold with no side actions or inserts.

Figure 1. Geometry 1, a domed cap

Geometry 2, an open impeller, is a little more complex. It still can be created in a two part mold but the vanes create a more complex casting situation. Geometry 2 is shown in Figure 2.

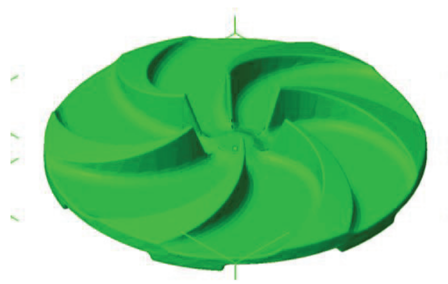

Figure 2. Geometry 2, an open impeller

Geometry 3, a closed impeller, is a step up in complexity and cannot be molded in a two part mold. Creating wax patterns will require either soluble or ceramic cores, resulting in multiple tools and increased cost. Geometry 3 is shown in Figure 3.

Geometry 4, a drone frame, is another step up in complexity and is a geometry that cannot be molded. Investment casting would require printed patterns.

Geometry 5, another drone frame, is a lattice structure designed to minimize the weight of the casting. The tight spacing of the lattice makes it unlikely that the pattern could be shelled without bridging. Even if it could be shelled, the thin web of the lattice would be difficult to fill. This geometry probably could only be created with metal printing.

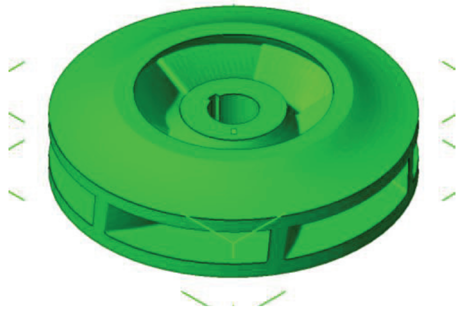

Figure 3 Geometry 3, a closed impeller

All five geometry files were sized so that the major dimension was four inches. To create the eight and sixteen inch sizes, the files were scaled by a factor of 2 and 4 respectively.

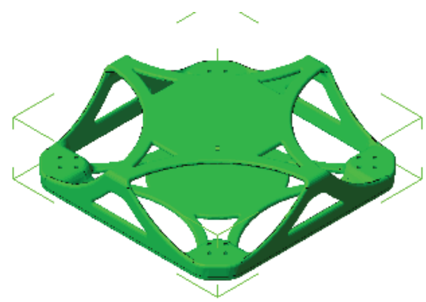

Figure 4- Geometry 4, a drone frame

Five levels of production volume were used; 1, 10, 100, 1000 and 10,000 copies.

These values of three major variables define a manufacturing space that includes the majority of the investment casting industry.

Figure 5 - Geometry 5, a lattice structure drone frame.

Several investment foundries were asked to quote each of the combinations of part complexity, part size and production volumes. They were asked to quote both conventional investment casting and hybrid investment casting using printed patterns.

For the conventional investment casting quotes, they were asked to estimate the cost of tooling rather than actually seek bids from tooling suppliers.

Printed pattern suppliers were asked to quote the same scenarios. The quoted prices were averaged for each pattern printing method and those averages were supplied to foundries for use in quoting hybrid investment casting prices. The foundries were asked to use the prices for whichever printing technology they were most comfortable with.

Several companies who provide metal printing services were also asked to quote printed metal components for the same scenarios.

For each scenario, all prices for conventional investment casting were averaged, as were the hybrid investment casting and metal printing prices. In each scenario, the lowest price was identified.

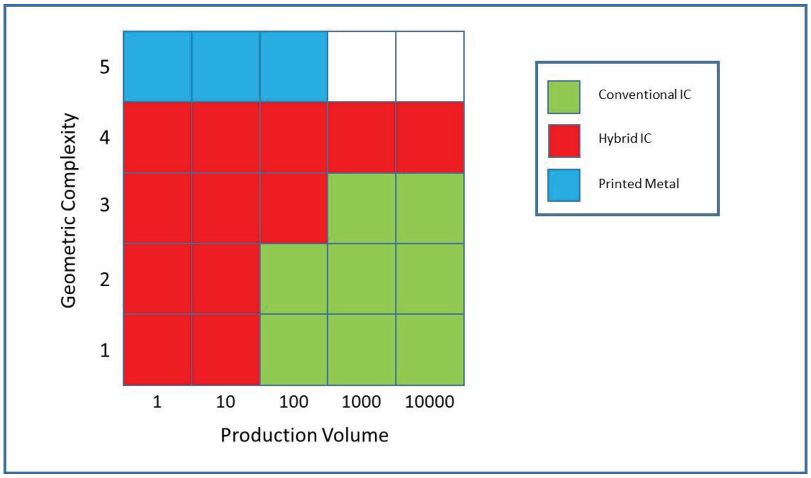

Figure 6 - Lowest methods of manufacture for 4 inch parts

Figure 6 illustrates the lowest prices for the 25 scenarios for 4 inch components. In those scenarios colored green, conventional investment casting with molded wax patterns was the least expensive method of manufacture. As expected, it is the least expensive method for all higher production volumes that can be done with conventional investment casting.

In those scenarios colored red, hybrid investment casting with printed patterns was the least expensive method of manufacture. For geometries 1 and 2, the simpler geometries, hybrid investment casting was least expensive for only very low quantities of 10 or less. Hybrid investment casting is least expensive up to 100 copies for geometry 3, which has a significantly higher tooling cost. For geometry 4, which can only be done with printed patterns or printed metal, hybrid investment casting is always the least expensive.

Metal printing is the least expensiv eoption only for geometry 5, which can only be done with printed metal. The suppliers did not quote the higher quantities of 1000 or 10,000. Those quantities would tie up their production for months.

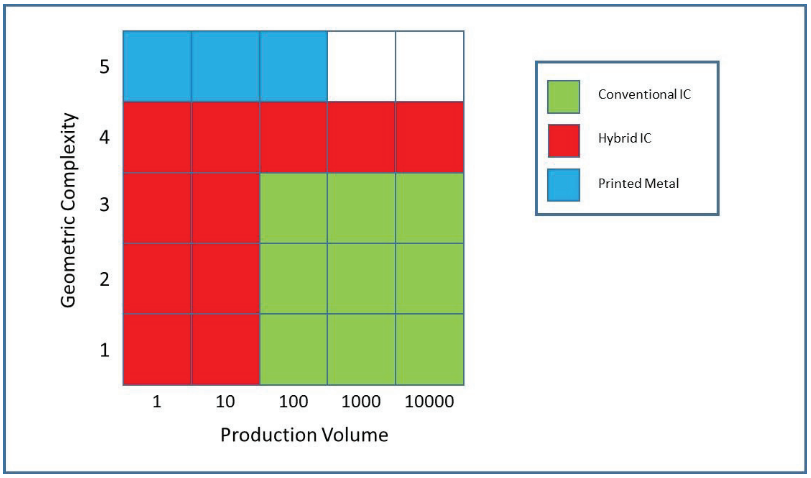

Figure 7. Least expensive method of manufacture for 8 inch parts

Figure 7 illustrates the lowest prices for the 25 scenarios for the 8 inch components. Very little has changed from the pricing for 4 inch components. The only scenario that changed was the 100 copies of geometry three in which conventional investment casting is now least expensive.

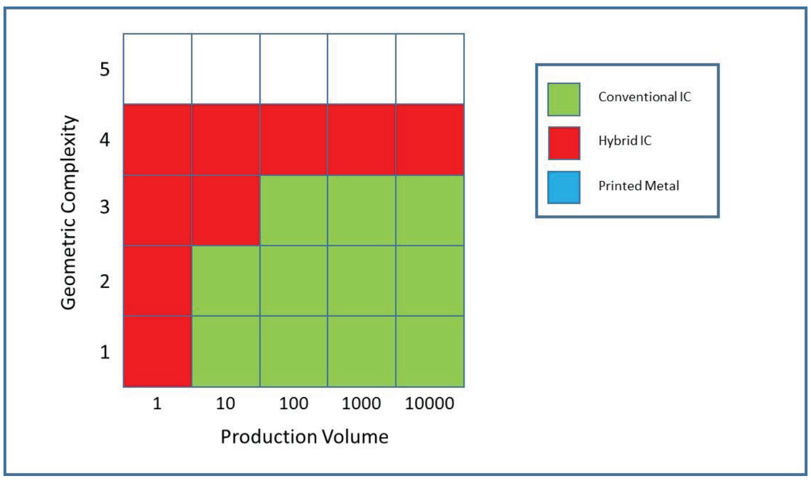

Figure 8 Least expensive method of manufacture for 16 inch parts

Figure 8 illustrates the lowest prices for the 25 scenarios for the 16 inch parts. There are a number of changes here. First, hybrid investment casting is less competitive on the larger parts. It is the least expensive method for only the first part on geometries 1 and 2. Printed metal does not show up at all. Current metal printers cannot handle parts this large.

Observations

From these results, several observations can be made:

1. Printed metal does not provide a lower cost method of manufacture for components larger than 4 inches which can be created with either conventional or hybrid investment casting.
2. Hybrid investment casting is most competitive for smaller part sizes. As the part size increases, the break-even quantity decreases.
3. Hybrid investment casting appears to be less expensive than metal printing for complex geometries that cannot be molded conventionally.

Effect of Reduced Prices for Metal Printing

There is no doubt that over time, the cost of metal printing will come down. The number of manufacturers of metal printers is increasing rapidly, increasing competition and putting pressure on prices. In addition, as the number of printers sold increases, economies of scale will reduce manufacturing costs. Also, we may well see new printing technologies introduced that will lower costs. If metal printing costs come down, will it become a lower cost alternative for part of the investment casting landscape?
To answer that question, all metal printing prices were reduced by 50%. All 75 scenarios were then re-examined to

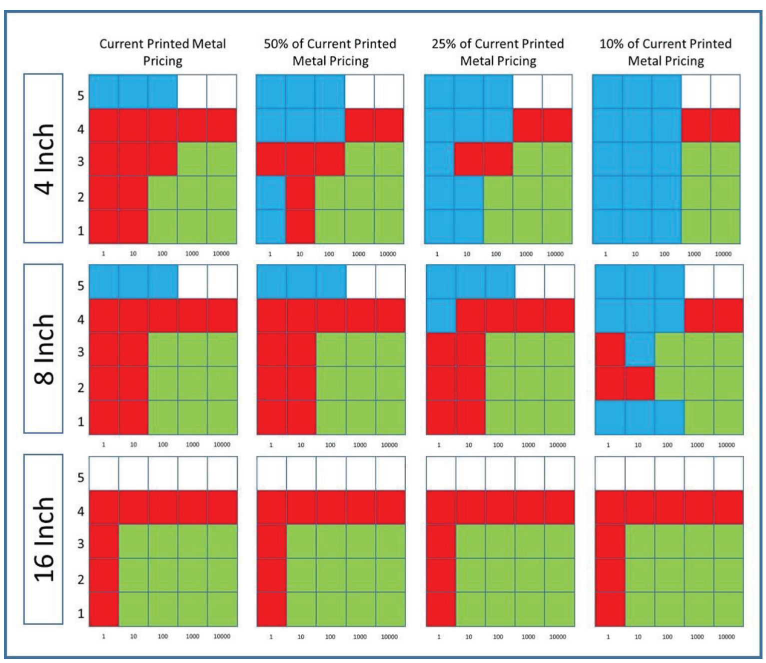

Figure 9. Affext of Reduced Pricing of Printed Metal Components

determine the lowest cost method for each. That analysis was repeated for price reductions of 75% and 90%. The results are shown in Figure 9.

Several observations can be made from these results:

1. A 50% reduction in metal printing prices has only a minor effect on the investment casting landscape.
    a. There are no changes in the low cost method for 8 inch and 16 inch parts.
    b. Metal printing becomes the lowest cost method for single copies of 4 inch parts with the lowest complexity.
    c. Metal printing is lower cost than hybrid investment casting for low quantities of castable but un-moldable 4 inch parts (Geometry 4).
2. A 75% reduction in metal printing prices has a relatively minor effect on the investment casting landscape
    a. Metal printing becomes the lowest cost method to create a single copy of the 8 inch version of Geometry 4.
    b. Metal printing is the low cost method of manufacture for most of the low volume production of the 4 inch part, regardless of complexity.
    c. There is no effect shown for 16 inch parts, but current machines cannot print parts that large. Once larger print capacity is available, there may be some impact on larger parts.
3. A 90% reduction in metal printing prices results in a much larger impact on the investment casting landscape.
    a. On the 4 inch parts, metal printing is the lowest cost method of manufacture for quantities of 100 or less regardless of complexity.
    b. On 8 inch parts, metal printing is the lowest cost method of manufacture or close to the lowest cost for quantities of 10 or less.

How much will metal printing prices come down? It is tempting to assume the same kind of price reductions seen in consumer electronics. Consider the drop in prices of video cassette recorders or personal computers over the first 10 or 15 years of life. Based on that, a price reduction of 90% might be possible.

However, there are significant differences between metal printers and consumer electronics. First, the majority of the printer is mechanical and there have not been similar reductions in the cost of mechanical components. Even with production scaling from tens of units per year to thousands, it is doubtful that there would be reductions of more than 50%. Secondly, a major portion of the cost of printed metal parts is the cost of raw materials. The majority of metal printers use powdered metal to create the parts. The powdered metal starts with the same material that foundries use for castings, but it is then further processed to create the fine powders needed for the printing process. As a result, powdered metal for printing sells at a significant premium to alloys for casting. For example, powdered titanium sells for about $150 per pound compared to $5 a pound for titanium for casting. Economies of scale may reduce that, but it will never be as inexpensive as the ingots foundries purchase. It is unlikely that prices will ever decline more than 50%.

Conclusions

1. Metal printing will not be competitive with conventional investment casting for components larger than 4 inches, quantities above prototype quantities, and moldable geometries. Normal production quantities will be least expensive to produce with investment casting.

Recommendations

1. The push toward light-weighting and the development of topology optimization tools will significantly increase the demand for castings which cannot be molded using conventional wax pattern tooling (example Geometry 4) and can only be cast using hybrid investment casting. This increase in demand will be at the cost of demand for conventional investment castings. It will be in the best interest of foundries to develop the capability to handle hybrid investment casting in production quantities, not just prototype.

INVESTMENT CASTING INSTITUTE

Advancing Sculpture

Rob Arps, Eyal Chernichovsky
Form 3D Foundry

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 2

ICI 64th Annual Technical Conference & Equipment Expo,
Marriott Cincinnati at Rivercenter, Covington, KY, 2017.

ADVANCING SCULPTURE

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ABSTRACT

The rise of digitally driven artistry is ubiquitous. It is a critical time to bridge the implications of the rise in three dimensional design to investment casting. Through a recent project called, *The Cloisters on the Platte*, we present our process called, *Advancing Sculpture* — a new framework of solutions to these obstacles. [1]

INTRODUCTION TO ADVANCING SCULPTURE

There is a vast resource of rising digitally driven artists who do not have exposure to current investment casting processes as well as the classical professionals who are unfamiliar with the benefits of advanced sculpture technologies. Our motivation is to address and shed light on these producer-consumer opportunities for professionals who are unaware of the possibilities of these processes for bringing their art into the world as tangible objects. In addition, an original physical sculpture may alternatively be rendered for malleability and scale in computational design. Digital technology has enhanced archival levels. The digital speaks to quantum computation which can in fact supersede and elevate the physical level of permanence. Our focus is to explore, develop, deploy and address the need to provide value-added resources.

[1] Cloisters on the Platte, Footage for Stations of the Cross. http://cloistersontheplatte.com/stations-of-the-cross/

How do we begin the process of creating a sculpture at Form 3D Foundry? When our 3D agency was commissioned to create *The Stations of the Cross* for *The Cloisters on the Platte*, we arrived at a crossroads.[2]

Fig. 1 Cloisters on the Platte, Omaha, Nebraska

Work for the project began in, 2014. Our 3D agency was involved in the full design process to complete the stations. Traditional applications involving classic enlargement require laborious mold making processes, post-processing of unfinished cast parts, assembly, and machining. Conventional methodology would have taken twelve years to create *The Stations of the Cross* from inception to completion.

Fig. 2-5 Sketch of *Station of the Cross*, pinch model figures, 3D Digital, and 3D Print Model

[2] On core competencies, see C.K. Prahalad, G. Hamel.

We were tasked with accomplishing this within three years, by August 2017. Utilizing traditional methods of sculpting was out of the question.

While maintaining our quality standards, our solution was to cut production time down by 75%. To do so, we coupled our traditional, classical method of artistry with inventive solutions.

Aiming to improve upon our own performance standards, we adopted automotive and aerospace technologies and invented an interwoven cache of systems to manipulate and use data output in such a way to print and mill in 3D. Form 3D Foundry is at the forefront of complex digital system implementation. There are currently no known simulations oriented to this process in the realm of fine art sculpting.

Our interest is to broaden the variety of techniques such as adopting new and different technologies to refine and redefine what it means to sculpt. It is about bringing practitioners from different fields together to share ideas and to foster new interactions and relations. Thus, the origin of *Advancing Sculpture*. We are headed in a new direction with new medium technology.

APPROACHING THE BIGGER MARKET

How do we approach a bigger market than ever before and introduce more art mediums to the investment casting processes? How do we go about educating this new generation in the investment casting market? How do we approach an expanded market and allow more art mediums to be introduced to investment casting?

Advancing Sculpture explores new mediums of art through the digital asset. We have the ability to generate, acquire and manipulate data through multiple avenues including 3D scanning, 3D modeling and analysis programs for different stages of the process.

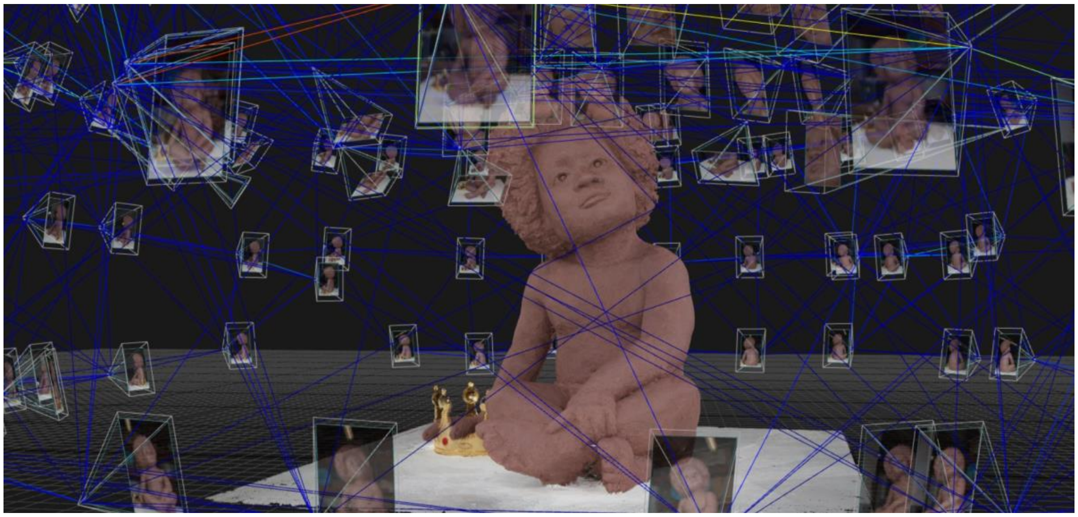


Fig. 6 Sculpture 3D Scanned

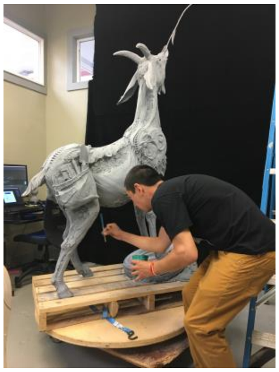
SCANNING[3]

- 3D Scanning
- Digital Data Archiving
- Life Scanning
- On-site Scan Services

Fig. 7. 3D Scanning

[3] F.I. Apollonio a , M. Gaiani a, *, W. Basilissi b , L. Rivaroli c. Photogrammetry driven tools. 53.

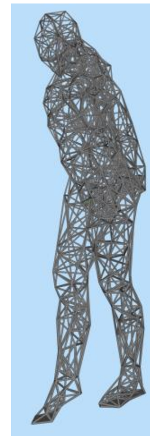
Fig. 8-9. Onsite scan service Fig 10. Digital Data Scanned

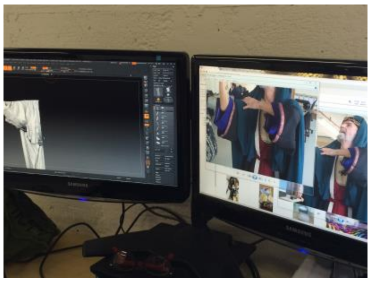


SCULPTING

3D Digital Sculpting[4]

- Tradition Sculpting
- Sculptural Enlargements and Reductions
- Theatrical Props





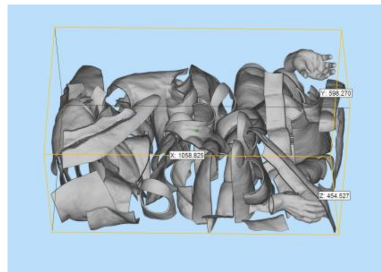


Fig. 10-12. Theatrical Props, Nested Enlargement and 3D Digital Sculpting

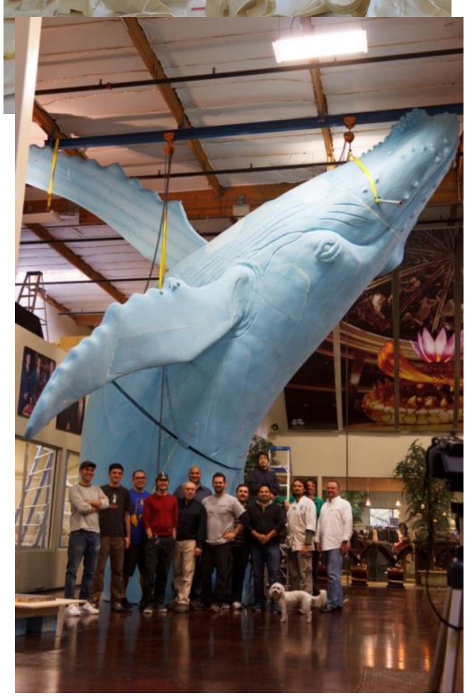
3D PRINTING

- Voxel 3D Printing
- Rapid Prototyping
- Complex Geometry and High Quality Surface Finishes
- Architectural Replications

Fig. 13-14. Voxel Prints

MACHINING

- CNC Milling
- Blue PIB & White Polystyrene
- Polyurethanes



[4] J. Voss Andreae.

- Wood

Fig. 15-17 CNC Milled White Polystyrene, 3D Printed Maquette and CNC Milling in Blue PIB

ARTIST SERVICES

- Sculptures from Artist's Concepts[5]
- Project Design Services
- Pattern Making for Sculptors and Jewelers
- Mold-Printing and Investment Casting

Fig. 18-20 Sculptures from Artists' Concepts and Mold Printing

BROADENING SOLUTION

We recognize collaboration is needed for greater speed and precision to help expand productivity and are exploring this landscape through a rapidly evolving economy. "The artist turns passionate explorations of the wonderful into works of art, and the scientist translates them into words and equations; but what drives innovation in science is inseparable from the elemental urge to express ourselves artistically."[6] The world is shifting with digital assuming permanence.[7]

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[5] B. Cooper Virtual Concepts to 3D Print.

[6] D. Gurnon, J. Voss-Andreae, J. Stanley (2013). "Integrating Art and Science in Undergraduate Education".

[7] Refer to digital archiving. G. Stiny, O. Gün, 8.

Computational design and complex geometries are now possible through the combination of digital design and investment casting. Rather than dealing with tangible objects, an original piece can now be built using 3D archiving through a digital file.

Form 3D Foundry uses additive manufacturing and has foundry-skilled production employees, all under one roof. This gives us the ability to deliver and manufacture quality sculpture on a previously unattainable timeline.

"What stands beyond [generic aphorisms] is the development of true dynamic models which exist today but due to high computational time/cost are only limited to small niche domains." We would like to open this floor through *Advancing Sculpture* so that "these obstacles are overcome [and] we may see the emergence of design computing environments where one could design interactively within a running simulation enchasing intuition about building statics, human behavior, etc."[8] As a 3D modeling-based agency functioning as a digitally proficient art-based investment casting foundry, Form 3D Foundry is the opposite of the norm. Achieving fidelity in artistic and organic shapes is uniquely labor intensive because of the density of data it is necessary for preservation. We're ideally suited to providing these services because of our experience and proficiency in digital asset management.

We conduct constant research on digital scanning, 3D design software and additive manufacturing chemicals for investment casting. We implement production practices from precision cast foundries and combining them into the fine art foundry process. We are leveraging the potential created by managing digital assets through design engineering and broadening new infrastructures for foundries.

The education of new technologies for potential clients, bureaus and the new generation edification of digital artists to investment casting markets is paramount. Our underlying quest is for the continuation of enhanced value and refinement of the fine art making process.

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BIOGRAPHY

ROB ARPS

Rob Arps is Founder and CEO of Form 3D Foundry. With over twenty years of classical artistry in traditional sculpting methods under his belt and fascination of science and technology, Rob's natural progression in 2000 integrated engineering tools and software from the automotive and aerospace industry into his art practice. This began improvements in cost and time without sacrificing quality. The results of increasing productivity and profitability, without compromising quality were immediate. Ultimately, technology created a sea change of radical improvements, unheard-of possibilities, and limitless potential. More importantly, Rob's unique and innovative use of technology has afforded him the opportunity to collaborate with some of the most creative and successful artists, architects, and design houses in the country.

EYAL CHERNICHOVSKY

As Form 3D Foundry Design Process Engineer and Production Program Manager, Eyal Chernichovsky is recognized for an inventive problem solving aptitude alongside analytical skills. Eyal finds that the simplest and most cost effective solutions in production and fabrication situations are the ones that he takes most satisfaction in because of the fundamentals they take to attain; a process geared towards a totality in additive manufacturing, computational design, a 3D dimensional brain (sometimes 4D), a deep understanding of the medium at hand and passion for art, design and engineering as one.

INVESTMENT CASTING INSTITUTE

3D Printed Ceramic Cores & Shells for Investment Casting Through Large Area Maskless Photopolymerization (LAMP) Technology

Dr. Suman Das
DDM Systems

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 3

3D Printed Ceramic Cores and Shells for Investment Casting Through Large Area Maskless Photopolymerization (LAMP) Technology

by
Dr. Suman Das
CEO, DDM Systems

Abstract:

LAMP is a breakthrough additive manufacturing technology enabling the 3D printing of ceramic cores and shells for investment casting. Originally developed for the direct digital manufacturing of turbine airfoils, the technology is applicable across all of investment casting. In LAMP, thin layers of a ceramic-loaded photocurable resin are sequentially cured using high resolution images in ultraviolet light using a scanning projection device. Macroscale green parts can be built with microscale features and excellent surface finish. Thermal post-processing involves binder burnout and sintering to achieve the final ceramic parts ready for casting. LAMP eliminates up to 7 of 12 process steps in investment casting, thereby dramatically reducing the cost and lead time for new castings. LAMP also enables advanced designs that are prohibitively expensive or impossible to make through traditional tooling. This presentation will cover the state-of-the-art of LAMP technology and an outlook towards future developments.

INVESTMENT CASTING INSTITUTE

Industry 4.0 for Investment Casting

Michael Kugelgen
MK Technology GmbH

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 4

Industry 4.0 for Investment Casting

The forth industrial revolution with autonomous and smart machines will change the working world fundamentally. In modern production and industrial plants nothing will remain the same and there will be drastic changes – this is at least what the intercedes of this trend are claiming. What does this mean for our Investment Casting world in general and in particular?

First of all we have to accept, that I.C. around the world is not the same. There is still a lot of manual technology in use. But on the other end there are fully automatic lines with several 6-axis Robots, automatic refill, shuttles and continuous monitoring and controlling. The second group is of course the more important one, when we start our discussion about Industry 4.0. And we have to split into two major fields: one is the production site and the output of I.C. parts.

The idea of Industry 4.0 can help to improve the quality, to shorten the development and delivery times and to reduce the scrap rate.

And the second interesting field for the new approach are all production machines and equipment, the robots, shuttles, the transfer stations and all moving and turning parts. Industry 4.0 can help to optimise the maintenance and to reduce costs, downtime and store capacity.

In a way, both areas belong together but we all have to find individual solutions when implementing the idea of Industry 4.0. And beside all the positive aspects we have to understand, that the new trend will also affect our working world and if we really think it to the very end, there might be a complete man less production and everything will be done by Robots. In this paper we will explain what might be possible and which solutions are already implemented.

Video: 4 minutes

INVESTMENT CASTING INSTITUTE

Prototyping Opportunities for Investment Castings, From an Ounce to 9,000 lb.

Will Jeffs, James Collins
Castings Technology International

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 5

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ICI 64th Technical Conference and Expo 2017 Paper

Prototyping Opportunities for Investment Castings, From an Ounce to 9,000lb.-

The advantages of prototyping options with respect to alloys group and weight.

MR William Richard Jeffs
MR James Michael Collins

1. Introduction

Prototyping activities in the manufacture of investment castings is no longer a novel approach to new part development or low volume manufacture. In 2017 we are at a climactic point in exploitation of prototyping within the investment casting industry. More and more foundries are setting up in-house capability; bureau services are being placed in strategic locations; and OEMs are developing novel and competitive materials and machines that are flooding into the market.

Castings Technology International (Cti) has attempted to keep at the forefront of innovations and developments within the investment casting and general casting sector. Investing in additive process such as 3D sand printing and Stereo-lithography for the previous 17 years has allowed the exploitation of casting prototyping at its infancy, whilst gaining the expertise and experience in utilising and building on the benefits inherent with such techniques.

2. Prototyping Technologies

There is a plurality of prototyping technologies on the market, all offering their own unique set of advantages and difficulties/limitations.

When prototyping for serial manufacture, it is not always practical or economical to operate a process which is directly comparable in behaviour; be it the thermo-physical behaviour of the pattern, interaction with the mould media, response to process conditions or removal prior to pouring.

2.1 Prototyping Technologies at Casting Technology International

2.1.1 Precision CNC Pattern

A novel moulding process developed by Cti for the prototyping of polystyrene investment casting provides a method for the production of low volume, high precision parts at poured liquid metal weights in excess of 9,000lbs.

A high density extruded polystyrene board is cut by a precision CNC 5-axis mill providing an exact replica of the casting. Due to the nature of the polystyrene, machined sections can be easily assembled to form an almost limitless size. The thermal stability of the pattern material means that critical dimensions can be maintained to tolerances far superior to any casting technology in its size range. Patterns are regularly in the size range of several feet, rather than several inches of the more typical investment casting.

The relative density of the polystyrene pattern material is less than $1/20^{th}$ that of wax and $1/15^{th}$ that of alternative polymer structures used in prototype printing. This completely changes the game in handling large tree's/assemblies.

As the polystyrene formulation is almost identical to that used for production volume tooled parts, this prototyping technique is 100% representative in all manners, allowing production to seamlessly commence without making assumptions on contraction factor conversion.

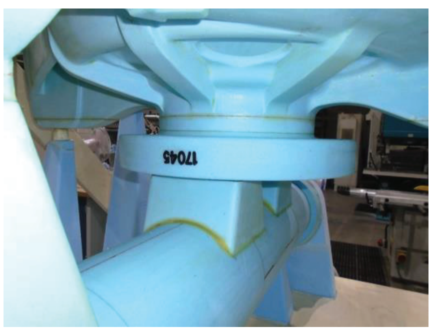

Figure 1- Precision Machined PS Replica (500kg Titanium Pump Casing)

Typical ash content after pattern removal is approx. 0.015%

2.1.2 Stereo-lithography

Hollow stereo-lithographic (SLA) patterns are commonplace in the investment casting industry. Over 17 years of experience in using such patterns for the manufacture of alloys ranging from Magnesium, Steels, Nickel-based alloys through to Titanium; Cti have pushed the boundaries and optimised the cast quality for some of the most demanding applications.

Through robust process control, novel processing techniques and integration as a prototype media for multiple production processes; SLA has gained the status as the prototype media of choice when economics, size and process-ability are concerned. Its compatibility with novel technologies means that rapid processing can be utilised taking advantage of the pattern materials tolerance to rapid shell making, whilst its ease of combustion (when conducted properly) enables even the most reactive of alloys to be poured into moulds produced by it.

Print speeds, volumes and costs are advantageous over many alternative technologies.

Geometric accuracies allow parts weighing just a few ounces to be produced.

Figure 2 - Siemens Baring Chamber (SLA Hollow Pattern and Finished Casting)

Figure 3 - Think Walled Exhaust Segment (Prototype SLA to Wax in Heat Resistant Ti-Alloy - Akrapovic)

The use of stereo-lithographic patterns was chosen to convert the Titanium travel lock bracket from a wax part to expanded polystyrene. The expensive process required to manufacture the 20" long cylindrical casting necessitated a soluble wax core weighing in excess of 22lbs and suffered from dimensional inaccuracies and excessively long wax processing times to name but a few problems.

Using 3D printing, a representative prototyping exercise was completed, with almost identical processing conditions, to provide a steam moulded polystyrene replica of the travel support. Due to the nature of the polystyrene, the cylinder could be made from two pattern halves, taking advantage of the ease in which the material can be joined with simple glues. The assembled patterns could then be processed at a fraction of the cost of its wax ancestor, producing a superior cast quality.

Without the ability to prototype in such a representative way as with SLA, the benefits would never have been demonstrated to the end user, which then allowed the re-sourcing for such a demanding and strategic Titanium casting.

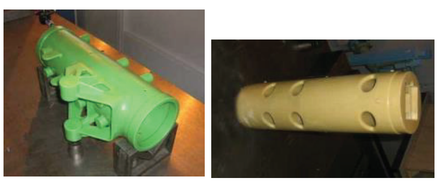

Figure 4 - Original Wax Pattern for Travel Lock Bracket with Enormous Soluble Wax Core

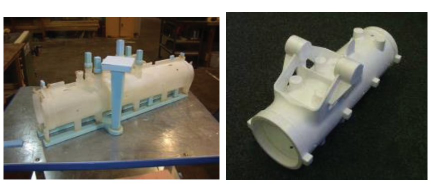

Figure 5 - Conversion Prototype Hollow SLA Pattern Prior to Low Cost Blown Foam Tooled Pattern

Typical ash content after pattern removal is approx. 0.25%.

With the low pattern density the physical ash content as % of part weight is very low, demonstrated by the use of this material in highly reactive titanium casting manufacture.

2.1.3 Hybrid Process

Most prototyping technologies still require features such as gating and risers; these can often be bigger in size than the parts being prototyped. Whilst the prototype method can be used to produce these additional aspects, it becomes a costly exercise when some of the features are such big heavy simple shapes (pour cups/runners etc.) As a result either poorly matched items are used, where tooling already exists, or badly hand shaped wax lumps are fashioned into shape. There is a tendency to use near enough, rather than the correctly dimensioned filling and feeding system required to optimise the as cast quality.

Cti have amalgamated their prototyping techniques and experience; by combining machined foam with 3D printed patterns. Not only does this offer a huge cost and time saving over a 100% printed assembly, but it also allows accurate one-off features to be incorporated and subsequently changed as new design iterations become available from the end user during the development phase.

Figure 6 - Hybrid Pattern Process Combining Precision CNC PS with SLA for Galleon Designed by Ursae Ltd. to Commemorate the Birthday of William Shakespeare

Figure 7 - Casting Produced from a Combination of Rapid Casting Techniques (Designed and manufactured by Ursae Ltd.)

Typical ash content of this hybrid process after pattern removal is approx. 0.1%

2.2 Alternative Technologies

Whilst not an exhaustive list, the following methods are described for purposes of appraisal through Cti's experiences from member foundries.

2.2.1 3D Wax Printing

3D wax printed parts are providing another level of accuracy and surface finish. Their relative similarities in behaviour to injected waxes provide processing advantages as well as a more accurate prototype conversion.

Whilst technologies progress quickly, limitations are still observed around process costs, cycle times and size limitations.

Typical ash content after pattern removal is approx. 0.02%

2.2.2 PMMA Powder Bed

Powder bed technologies using materials such as PMMA are taking a big market share within the investment casting industry.

Typical ash content after pattern removal is approx. 0.3% this is a significant amount when factoring in the relative density of the PMMA

As with other materials detailed, specific processing techniques are required to manufacture castings from this route when compared to conventional wax patterns. Several foundries have reported actual figures relating to machine economics, material costs and part quality. These have very much been contradictory to previously published information. A comparison of key process performances will be presented alongside this paper.

3. Summary

There is no simple solution to every foundry's prototyping needs.

When size ranges are required from ounces to 1,000's of lbs, having a variety or hybrid approaches to prototyping is advantageous.

The use of stable and low cost prototyping process allows economical prototyping with direct compatibility/transferability to production routes for parts exceeding several 1,000lbs and beyond.

4. References and Acknowledgements

Acknowledgements

The technique used for manufacturing castings from machined and moulded polystyrene foam is a proprietary technology named Replicast® licensable from Cti.

Many thanks to Siemens, BAE systems, Akrapovic and URSAE Ltd for their cooperation in this publication.

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INVESTMENT CASTING INSTITUTE

Permeability Panel Discussion

Julie Markee – Key Process Innovations
Nip Singh – S&A Consulting Group LLP
Craig Lanham – Retired Ceradyne, Inc. a 3M Company
Taylor Thornhill – O'Fallon Casting
Thad Nykiel – Bescast, Inc.

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Panel Discussion

Panel Discussion on Permeability

The effect of permeability is an often ignored as it is often times one of the least understood shell properties. Most foundries know they need permeability but they might not know what factors are impacting permeability and what to do if casting quality points towards issues around permeability. As a result of this panel discussion, foundries will gain a greater understanding of permeability and specific areas within the process which can impact permeability.

The purpose of this panel is to discuss:

- What is permeability
- Why permeability is important
- Different methods for measuring permeability – Hot and Green
- Factors which can impact permeability

The panel will be moderated by Julie Markee (Key Process Innovations) and will include presentations from:

- Thad Nykiel, Bescast, Inc.
- Taylor Thornhill, O'Fallon Casting
- Craig Lanham, Retired from Ceradyne, A 3M Company
- Nip Singh, S&A Consulting Group LLP

INVESTMENT CASTING INSTITUTE

A Comprehensive Study of Thermo-Physical Properties of Investment Shell

Dr. Mingzhi Xu
Missouri University of Science & Technology

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 6

A Comprehensive Study of Thermo-Physical Properties of Investment Shells

Mingzhi Xu
Missouri University of Science and Technology

ABSTRACT

Investment shell molds are typically built up with metastable amorphous silica binder and may include fused (amorphous) silica flour as filler and crushed fused silica grains as stucco. These metastable amorphous (non-crystalline) materials can crystallize (devitrify) at elevated temperature during industrial process and the amount of transformed amorphous phase depends on temperature, time at temperature, and the presence of mineralizers. The degree to which these amorphous phase materials devitrify during the process will affect the thermo-mechanical properties, which controls the solidification and ceramic shell integrity. In this article, influences of firing temperature on the thermo-mechanical properties of silica-based shell molds were investigated. The thermal properties were also correlated to the degree of phase transformations, which can occur during sequential heating/cooling cycles in investment casting processing.

Keywords: investment shell, firing temperature, phase transformation, thermal property, mechanical property

INTRODUCTION

Investment shell molds have been widely used to produce near-net shape castings, especially with complex geometry and thin sections[1-6]. Process simulation of the investment casting is often used in modern foundry practice because it is able to predict and eliminate many types of casting defects, such as shrinkage, porosity, and hot tears. Accurate representation of the thermal properties of the ceramic shell is critically important for realistic simulation of casting solidification.
Many researchers have attempted to accurately determine the thermal properties of shell molds utilizing different methods. Numerous equations have been proposed since 1939 to account the effect of porosity on thermal conductivity[7-13]. However, those equations worked only for certain materials or types of porosity within a very limited temperature range.

Several experimental and simulation methods have been developed to determine the thermal properties of the highly porous investment shell mold material. The hot wire method was used to measure the thermal conductivity of industrial shell materials[14-16]. However, the hot wire method assumes that the material is isotropic in all radial directions and thus is not well applicable to investment shells[17]. The layered structure in investment shells requires a more directional measurement technique.

A laser flash method for directional measurements of thermal diffusivity and specific heat capacity was first introduced by Shinzato and Baba[18-19]. This method uses thin (1-3 mm thickness) specimens and could be applicable for measuring the properties of thin layers. Using this technique, Connolly[20] and Konrad[21] have measured the thermal properties of investment casting shells up to 1300°C. More recently, Sabau[17] pointed out that the laser flash method had low accuracy when measuring the thermal properties for investment casting shells. It was found that a thin fused silica shell specimen had a suitable thermal response time during measurement but the results could be affected by the unimpeded laser light penetration through the shell due to large voids in the structure. On the other hand, thick fused silica shell specimen could not be used since it does not have a suitable response time during the measurements. Also, the open pores on the specimen surface variably reduce the actual thickness of the specimen which creates significant uncertainties in the measurement. Garcia et al.[22] presented a method to solve this problem by attaching two thin copper disks to a porous specimen to ensure a known effective thickness and eliminate the penetration of the laser. However this method is not applicable for a brittle investment ceramic shell. Xu et al.[23-24] utilized a three dimensional optical profiler to determine the effective thickness of the specimen and improved the accuracy of laser flash method for measuring thermal properties of a specimen with porous surfaces.

The inverse method is another way to estimate the “real-time” thermal properties of the entire shell during casting solidification. The inverse method is based on matching the real cooling curves obtained from the casting and the shell during the process to the computer simulated cooling curves by varying the properties of interest[23-28]. In this method, the thermal properties measured from the laser flash method were used as the starting point for the inverse simulations. A well-established starting point near the final value is beneficial to get the best agreement with the physics from the optimization used for the inverse method. In the inverse simulations of unsteady state heat transfer in the casting/shell/environment system, some well-defined thermal properties are also used as the input to help calculate the unknown properties.

The thermal properties obtained from the inverse method are considered as the realistic properties for simulation purpose. However, the laser flash method can be treated as an ideal method for measurement of near steady state thermal properties because a thin specimen is thermally equilibrated before taking measurement. The laser flash method is suitable for capturing property changes due to process changes at fixed test temperature. This test facilitates understanding of the mechanism of property changes by relating the properties to specific temperatures.

It is reasonable to expect that the shell processing thermal history is an important factor, in addition to ceramic composition, which influences the investment shell thermo-physical properties. Generally, a shell mold, constituting a mixture of a set of thermodynamically metastable ceramic ingredients, is exposed in several thermal cycles before the final casting is poured. These thermal cycles may include (i) drying and aging of wet mold (ii) heating for pattern removal, (iii) sintering during firing, (iv) an additional reheating before pouring and, finally, (v) heating/cooling cycle during pouring liquid metal, casting solidification, and cooling. Considering that the colloidal silica binder as well as the flour filler and most stucco ceramics are amorphous to a significant extent, the degree to which the amorphous to crystalline transformation takes place during the processing also has a great effect on the thermal properties of ceramic shell[29-31].

It is implied by the procedures of industrial practices that the thermal history has great direct and indirect effects on investment shell properties and casting quality; however, only restricted studies have been done to quantify these effects. Mahimkar et al.[30] measured the heat capacity of different shell systems exposed to different thermal histories and these authors drew a correlation between the change of the heat capacity and the silica phase transformations. Meulenberg et al.[31] detected the phase transformation of silica binder from being completely amorphous in the unfired condition to cristobalite within the usual firing temperature range between 900°C and 1500°C, in which range zircon remains stable.

In this study, influences of firing temperature on the thermal and mechanical properties of silica-based shell molds were investigated. The thermal properties were also correlated to the degree of phase transformations, which can occur during sequential heating/cooling cycles in investment casting processing.

EXPERIMENTAL

SHELL BUILDING

Expanded Polystyrene (EPS) foam pattern was used in this study. Colloidal silica binder, -200 mesh fused silica flour and 30/50 mesh fused silica stucco were used to build shells. The slurry consists of 33 wt. % of silica binder and 67 wt. % of silica flour. The slurry was mixed for 24 hours to achieve constancy. The viscosity of the slurry was tested using a Brookfield DV-II+ Pro viscometer equipped with a LV3 spindle operating at 30rpm. The dynamic slurry viscosity was maintained at 1100±100cP for the prime coat and 600±50cP for the back-up and seal coats.

The foam patterns were lightly abraded using a 1200-grit sandpaper to remove surface texture differences between cut and uncut surfaces. The patterns were submerged in the slurry for twenty seconds. Then the patterns were removed and excess slurry was allowed to naturally drip off for one minute. During drip removal, patterns were rotated around the vertical axis at a speed of 10rpm with the dipped end facing down and oriented at a 45° angle from the vertical axis. Stucco was then applied onto the slurry coat in a rainfall sander. A uniform distribution of stucco was achieved by turning the samples at a constant speed until no additional stucco would adhere to the wet surface. The samples were allowed to air dry for at least four hours before the next layer was applied. For each sample, one prime coat, five back-up coats and one seal coat were applied.

PATTERN REMOVAL AND SHELL FIRING

After being dried for minimum one additional day in a controlled humidity room, the foam pattern was carefully burned out by a propane torch under a hood. Then the shells were put into a cold laboratory chamber furnace and heated up at a rate of 30ºC/min to different firing temperature individually (600°C (1112°F), 850°C (1562°F) or 1000°C (1832°F)), then held for one hour prior to testing. The shells were allowed to cool down in the chamber overnight. They were subsequently tested at temperatures of 200°C, 400°C, 600°C, 800°C, 1000°C and 1200°C by laser flash and X-ray diffraction using the temperature cycle shown in Figure 1A. The composition of each layer of the shell is given in Table 1.

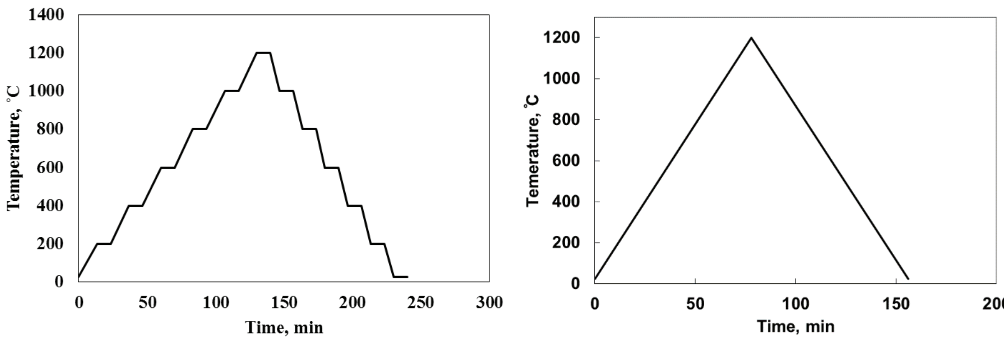
DEVELOPED LASER FLASH METHOD

Laser flash was used to determine the specific heat capacity and the thermal conductivity of the shells. A graphite disk was used as the reference material. The specimens were machined to 12.7 *mm* by 12.7 *mm* by about 2 *mm* thick disks. To insure similar emissivity, the front and rear faces of both the reference and the test specimens were covered with a sprayed graphite coating. Surface roughness due to porosity in the specimen was measured by a 3-D optical profiler.

Table 1. Composition of the silica based investment shell.

Coat (Number of layers)	**Slurry**	**Fused silica stucco particle size, mm**
Prime coat (one)	Colloidal silica (1-100 *nm*) + fused silica flour (2-20 μm) (1:2 by weight). Viscosity 1100cP±100cP	0.3-0.6
Backup coats (five)	Colloidal silica (1-100 *nm*) + fused silica flour (2-20 μm) (1:2 by weight). Viscosity 600cP±100cP	0.3-0.6
Seal coat (one)	Colloidal silica (1-100 *nm*) + fused silica flour (2-20 μm) (1:2 by weight). Viscosity 600cP±100cP	N/A

The effective thickness of each specimen was determined based on total thickness and the surface roughness adjustment. The effective thickness was used to calculate thermal properties[19, 23-24]. The samples were placed into a cold furnace and heated to 1200°C (2192°F) at a heating rate of 15°C/min (27°F/min) then cooled to room temperature at 30°C/min (54°F/min). During the thermal cycle, laser flash was performed at every 200°C (360°F) from 200°C (392°F) to 1200°C (2192°F) upon heating and cooling, after the samples were held for 10 minutes at each elevated temperature (Figure 1a).



(a) (b)

Figure 1. The temperature regime used for high temperature tests: (a) X-ray diffraction and laser flash method, 15°C/min (27°F/min) heating and 30°C/min (54°F/min) cooling rates, with a 10 min hold at each elevated temperature; (b) DTA, 15°C/min (27°F/min) continuous heating and cooling rates

HIGH TEMPERATURE X-RAY DIFFRACTION
X-ray diffraction (XRD) was performed using a diffractometer. The shells were finely powdered to minus 100 mesh and loaded on a platinum strip (Pt diffraction peaks were shown in Figure 2). The specimens were heated in the chamber at a 15°C/min (27°F/min) heating rate up to 1200°C (2192°F) then cooled to 25°C (77°F) with a 30°C/min (54°F/min) cooling rate. During the heating and cooling process, the specimens were held for 10 minutes at temperature from 200°C (392°F) to 1200°C (2192°F) with an interval of 200°C (360°F) (Figure 1a). At the end of each hold, XRD data were collected in a step 2θ-scan mode from 10° to 70° with a total counting time of five minutes, using an incident wavelength of 1.54 Å. A scan was also performed at room temperature before and after the thermal cycle.

DIFFERENTIAL THERMAL ANALYSIS
Differential thermal analysis (DTA) was performed. Before testing, the samples were dried at 110°C (230°F) for 1 hour. High purity Al_2O_3 powder was used as the reference material. Experiments were performed under air atmosphere at a flow rate of 50 mL/min. Samples were heated from room temperature to 1200°C (2192°F) at a heating rate of 15°C/min (27°F/min) and then cooled to room temperature at the same rate (Figure 1b).

SPECIFIC SURFACE AREA.
Brunauer–Emmett–Teller (BET) method was used to determine the specific surface area of the shell samples. Colloidal silica binder was dehydrated and hand crushed using a mortar and pestle to a certain size for which the equivalent spherical surface area would be orders of magnitude below the measured value of the BET method. The crushed silica binder was fired at different temperatures, 600°C (1112°F), 850°C (1562°F) and 1000°C (1832°F), for 1 hour. Afterwards, the powder was well blended and dehydrated at 120°C (248°F) for another 2 hours before the test. The specific surface area in m^2 per gram of powder was measured at the temperature of liquid nitrogen.

DENSITY AND POROSITY.

The bulk density and open porosity accessible to water of the shells were measured using Archimedes method[32]. The same specimen were then crushed and the true density was measured by a *He*-Pycnometer, in which all of the pores were filled by *He* and the true volume of the powder can be measured.

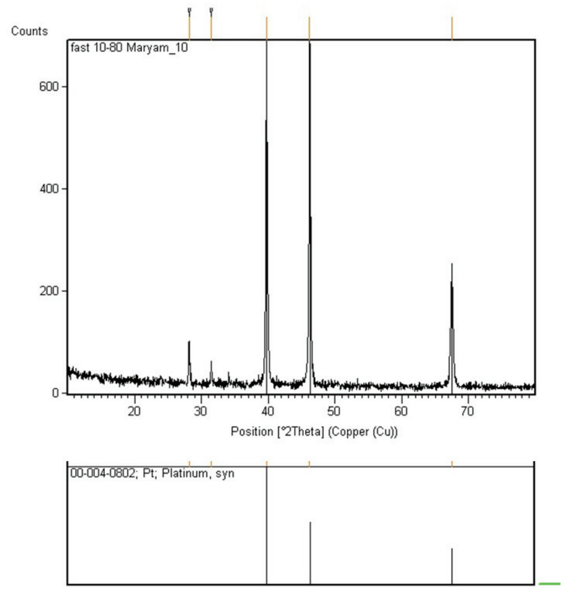


***Figure 2.** X-ray diffraction pattern of a reference platinum strip at room temperature showing some spurious indications at 2θ of 28°, 31° and 34° which were excluded from subsequent measurements*

THREE-POINT FLEXURAL TEST.
Moduli of Rupture (MoR) of the shells were measured according to ASTM C1161[33] using a three point bend test apparatus at room temperature after the shells were fired at the elevated temperatures for one hour.

RESULTS

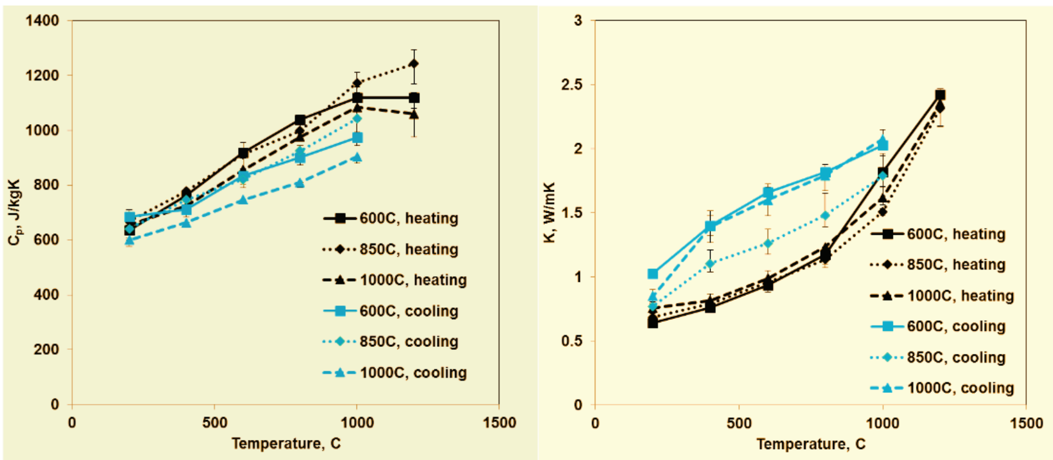
DENSITIES AND POROSITIES
Table 2 shows the densities and porosities of shells under different firing conditions. Measurements were made at room temperature after firing the shells at different temperatures. These results indicate that the firing process decreases closed and total porosities. It is found that a higher firing temperature results lower closed and total porosity values due to a higher degree of sintering.

***Table 2.** Room temperature density and porosity of shells fired at different temperatures*

Pre-firing temperature, ˚C (˚F)	**Bulk density, g/cm³**	**True density, g/cm³**	**Open porosity accessible to water, %**	**Closed porosity, %**	**Total porosity, %**
Unfired (green)	1.77±0.04	2.64±0.03	16.2±0.2	16.6±2.1	32.8±1.9
600 (1112°F)	1.73±0.03	2.55±0.02	18.4±0.1	13.8±1.5	32.1±1.4
850 (1562°F)	1.83±0.02	2.60±0.01	17.1±0.1	12.4±0.9	29.5±0.8
1000 (1832°F)	1.76±0.02	2.42±0.01	16.8±0.1	10.7±0.8	27.5±0.7

EFFECT OF FIRING TEMPERATURE ON SHELL THERMAL PROPERTIES.
The specific heat capacity (C_p) and the coefficient of thermal conductivity (K) of the shells subjected to different firing temperatures were measured by the developed laser flash method. The properties of shells upon heating and cooling during the measurements are plotted in Figure 3. In all of the shells, both C_p

and *K* values increase with increasing test temperature. During the heating, the thermal conductivity of the three shells are similar, while the shell fired at 850°C (1562°F) has a decreased thermal conductivity during the cooling cycle. Differences on the heat capacity among these three shells were noticed after the shells were heated to 1200°C (2192°F). These discrepancies in C_p and *K* values indicate a certain amount of devitrification happens during this particular test thermal cycle, which can have an effect on the thermal properties.



(a) (b)

Figure 3. Heat capacity (a) and thermal conductivity (b) of fired shells measured from the laser flash method; firing temperature and thermal cycles are indicated in the legends

EFFECT OF FIRING TEMPERATURE ON SHELL MECHANICAL PROPERTIES.

Room temperature three-point bend test results (Figure 4) show that after firing the shell at 600°C (1112°F), there isn't any significant sintering, thus the modulus of rupture (MoR) of the shell doesn't have a noticeable change, compared to the green shell. However, the MoR of the shell increases at relatively higher firing temperatures, 850°C (1562°F) and 1000°C (1832°F), due to an extended amount of sintering. Nevertheless, at an even higher firing temperature of 1200°C (2192°F), the MoR decreases significantly. This can be the result of the devitrification where the difference in volume changes introduces more defects as the shells cool down after being fired.

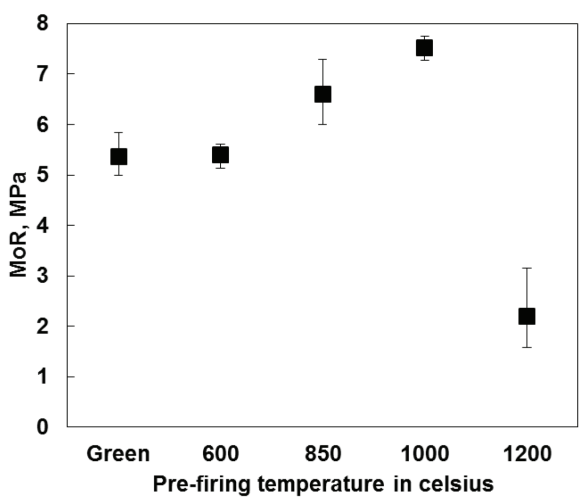
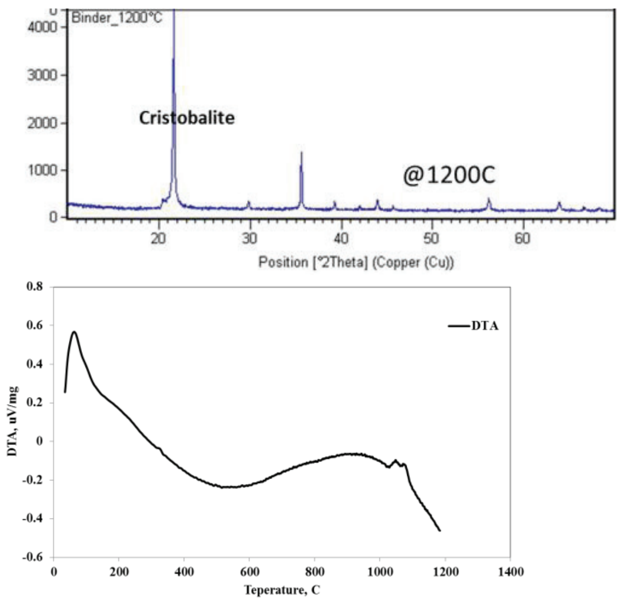


Figure 4. Modulus of Rupture (MoR) of silica shell molds fired at different temperature; tests were performed at room temperature

SILICA BINDER DEVITRIFICATION TEMPERATURE.

To identify the components of the shell which are predominant with respect to the phase transformation, high temperature XRD tests were performed individually on each of the components used for investment shells, including silica binder, fused silica flour, and fused silica stucco. Devitrification was only found in the silica binder at temperatures above 1000°C (1832°F), while the other components remained amorphous during the test up to1200°C (2192°F) (Figure 5a). This is because silica binder has a much smaller particle size (1-100 nm) than the other components (2 μm – 0.6 mm). Thus silica binder has a higher surface area to volume ratio which could provide an additional activation energy component as well as an easy transport path for transformation. The DTA results (Figure 5b) also indicate that the silica binder starts devitrification at around 1000°C (1832°F). These data are supported by a study[29] which also found that amorphous silica transformed to cristobalite at 1000°C (1832°F).



(a) (b)

Figure 5. XRD at 1200°C (2192°F) shows the presence of cristobalite (a) and DTA test shows the devitrification temperature is around 1020°C (1868°F) (b)

PHASE TRANSFORMATION DURING FIRING AND PRE-HEATING.

According to a typical investment casting process sequence used in many high production volume investment casting foundries, the shells are fired after pattern removal, cooled down, and inspected. Then shellsare subjected to a second short pre-heating, just before pouring. Last pre-heating stage is necessary to minimize the heat loss during pouring, allowing liquid metal to fill the narrow cavities of the hot mold. These multiple heating/cooling cycles will affect the solid phase transformations in the shell.

<u>After firing cycle</u>

Phases that are present in the shells after the firing cycles were studied by XRD. In this case, XRD tests were performed at room temperature on the shells fired at different temperatures. It is found (Figure 6) that the shell fired at 1000°C (1832°F) has a crystalline peak, while other shells (green and fired at lower temperatures) have just amorphous phase. In the case of a multi-component shell, at a firing temperature of 1000°C (1832°F), phase transformation in silica binder starts and the cristobalite may nucleate at the boundary with silica flour, however the silica stucco is inert. The broad crystalline peak in Figure 6(d) indicates that most of the crystallites have a very small grain size.

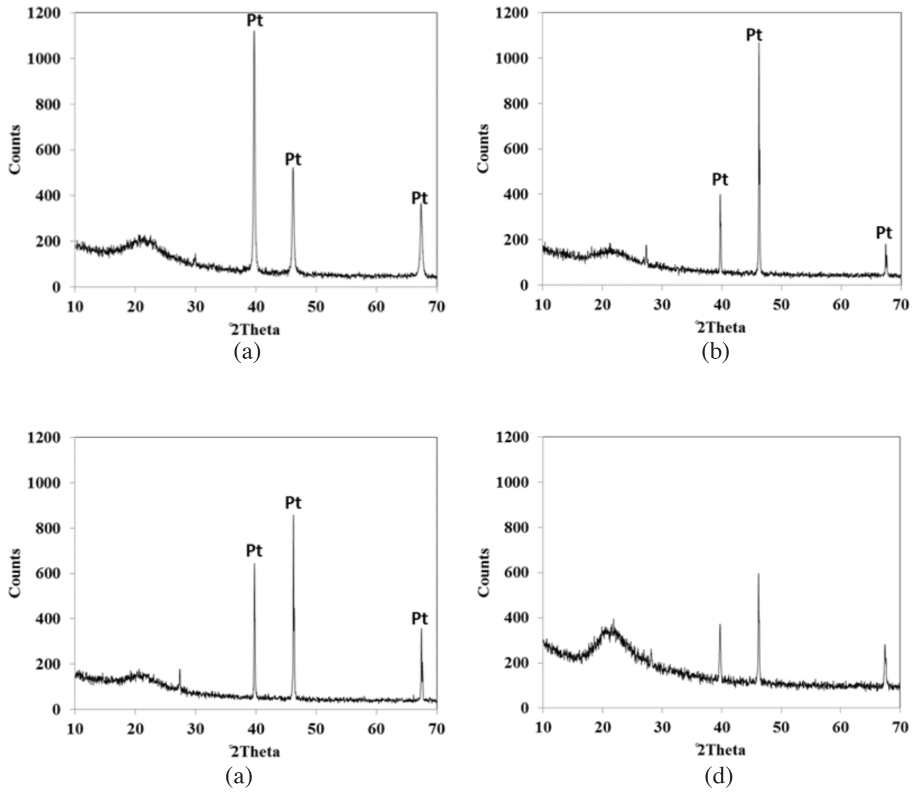


Figure 6. Room temperature XRD patterns of ceramic shell fired at different temperatures: (a) green, not fired, (b) 600°C (1112°F), (c) 850°C (1562°F), and (d) 1000°C (1832°F)

Dynamic phase transformation during reheating

After the shells are fired, the shells were reheated up to 1200°C (2192°F) and XRD tests were performed at 1200°C (2192°F). As shown in Figure 7, the green shell and shell previously fired at a low temperature (600°C or 1112°F) have a very sharp peak of cristobalite, while the shell previously fired at 850°C (1562°F) and reheated after that doesn't have much of phase transformation. In the shell fired at 1000°C (1832°F), the cristobalite, which has already formed during the firing process, grows to larger particle sizes during the subsequent 1200°C (2192°F) reheating cycle.

Specific Surface Area Change during Firing and Reheating

During firing and reheating, sintering as well as devitrification could occur simultaneously in the shell. The amount of sintering can be represented by the direct measurements of the specific surface area change on the silica binder. The specific surface area was measured after the silica binder was fired at different temperatures. Measurements were repeated after the fired binder was reheated to 1200°C (2192°F) and held for one hour.

As shown in Figure 8, after firing shells at different temperatures, the binder fired at 600°C (1112°F) does not exhibit significant change in the specific surface area, which indicates that a minimum amount of coarsening takes place at this temperature. When the binder was fired at 850°C (1562°F), a small reduction (20%) in specific surface area is observed and this could be the result of vitreous sintering without devitrification. A dramatic decrease in specific surface area (from 53 m^2/g to 0.1 m^2/g), after firing the colloidal silica binder at 1000°C (1832°F), shows a significant extent of sintering.

When the fired colloidal silica binder is reheated to 1200°C (2192°F), it is found that the surface areas of all of the colloidal silica binders are reduced to the similar level, indicating that firing temperature doesn't have a big effect on the sintering when the binders are subjected to a higher reheating temperature.

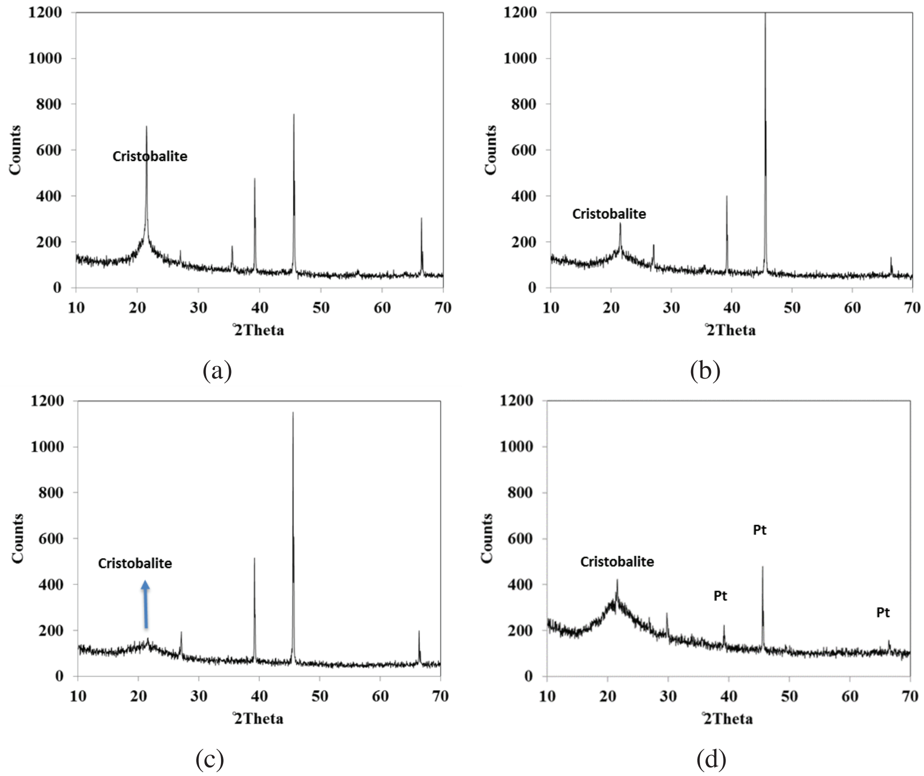


Figure 7. XRD patterns at 1200°C of the shells which are reheated to 1200°C after different thermal processing: *green condition (a), preliminary fired at 600°C (b), 850°C (c), and 1000°C (d)*

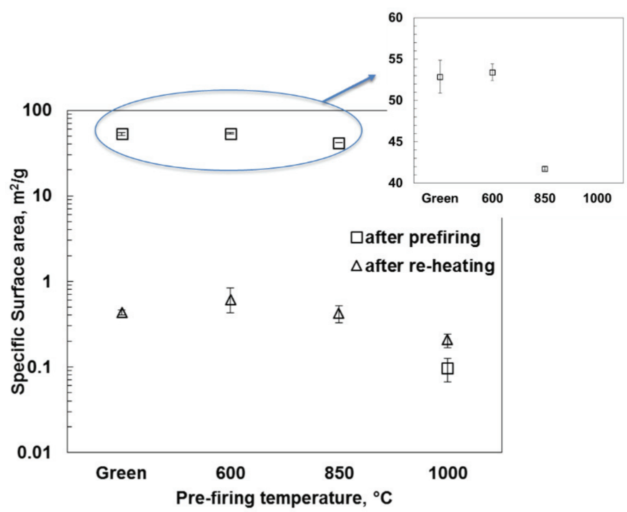


Figure 8. Specific surface area of the colloidal silica binder after being fired at different temperatures; measurements were repeated after the fired binder samples were reheated to 1200°C (2192°F) and held for one hour

DISCUSSION

EFFECT OF FIRING TEMPERATURE ON SPECIFIC SURFACE AREA AND PHASE TRANSFORMATION

DTA results (Figure 5b) show that silica binder is the only constituent that devitrifies at 1000°C (1832°F). Thus when firing the shell at 1000°C (1832°F), it is just enough to start the devitrification kinetically, but at a rather slow rate. Thus only small crystalline sizes of cristobalite is found from the XRD tests (Figure 6d). The coarsening was still predominant during firing at this temperature, thus a dramatic specific surface area loss is noticed (Figure 8). Thermodynamic software FactSage 6.4 was used to calculate the Gibbs free energy change (ΔG) of one mole of silica from amorphous to cristobalite (h) at 1200°C (2192°F): ΔG = -2500J. Taking the surface energy of amorphous silica as 0.26 J/m^2 [34], the surface energy stored in one mole of amorphous silica binder decreases by almost 1000J when surface area is reduced from 53m^2/g (green state) to 0.1 m^2/g (fired at 1000°C or 1832°F). This suggests that surface energy could provide a significant component of the activation energy for the devitrification reactions. Additionally, this surface area lost will impede the reaction rate for the phase transformation since a higher surface area provides a more favorable reaction path. Consequently when reheating the shells (previously fired at 1000ºC or 1832°F) to 1200°C (2192°F) after firing, less amorphous silica devitrifies than in a shell fired at lower temperatures. However the cristobalite previously formed during firing could grow to a larger grain size due to grain growth, which is consistent with a sharper cristobalite peak being observed in XRD (Figure 7d). Similarly, when firing the shell at 850°C (1562°F), the specific surface area decreases by more than 20% (Figure 8) due to sintering, and less devitrification takes place when that shell is reheated to 1200°C (2192°F) than would occur in shells fired at a lower temperature. The shell fired at 600°C (1112°F) doesn't have any significant sintering thus retains similar specific surface area compared to the green shell. When reheating shell fired at 600°C and the green shell, sharp cristobalite peaks were obtained on the diffraction patterns.

In summary, a higher firing temperature, in the temperature range below the amorphous silica devitrification temperature, decreases the reactivity of the binder towards devitrification or the rate of devitrification.

EFFECT OF FIRING TEMPERATURE ON THERMAL PROPERTIES.

The atomic-scale disorder present in the amorphous silica causes its thermal conductivity to be lower than the conductivity of the cristobalite, because the structural disorder impedes the motion of the mobile photon thus lowering the thermal conductivity. When correlating the XRD results with the thermal properties measured by the laser flash method, it is noticed that the shell fired at 600°C (1112°F) has the greatest amount of cristobalite formation, subsequently the highest thermal conductivity. The shell which has been fired at 850°C (1562°F) exhibits a very limited amount of cristobalite formation and shows a lower thermal conductivity. The shell fired at 1000°C (1832°F) not only has some amount of devitrification during the firing process, but when being reheated to 1200°C (2192°F), the already formed cristobalite grows to larger grain sizes. This eliminates some grain boundaries that impede the photon movement, thus higher thermal conductivity values are expected.

In the case of specific heat capacity, the shell fired at 850°C (1562°F) doesn't devitrify as much as the shells fired at 600°C (1112°F) and 1000°C (1832°F), thus the heat capacity values increase with increasing temperature within the temperature range from 200°C to 1200°C (2192°F), similar to the behavior of amorphous silica. However, the shell fired at 600°C (1112°F) devitrifies at above 1000°C (1832°F) during the laser flash measurements. The transformation from amorphous silica to cristobalite is an exothermic reaction. The heat generated in this transformation is 9500 J/mole or 158 J/g. In other words, assuming the heat capacity of silica at 1 J/gK, this energy is enough to increase the temperature of one gram silica by over 150°C (270°F).

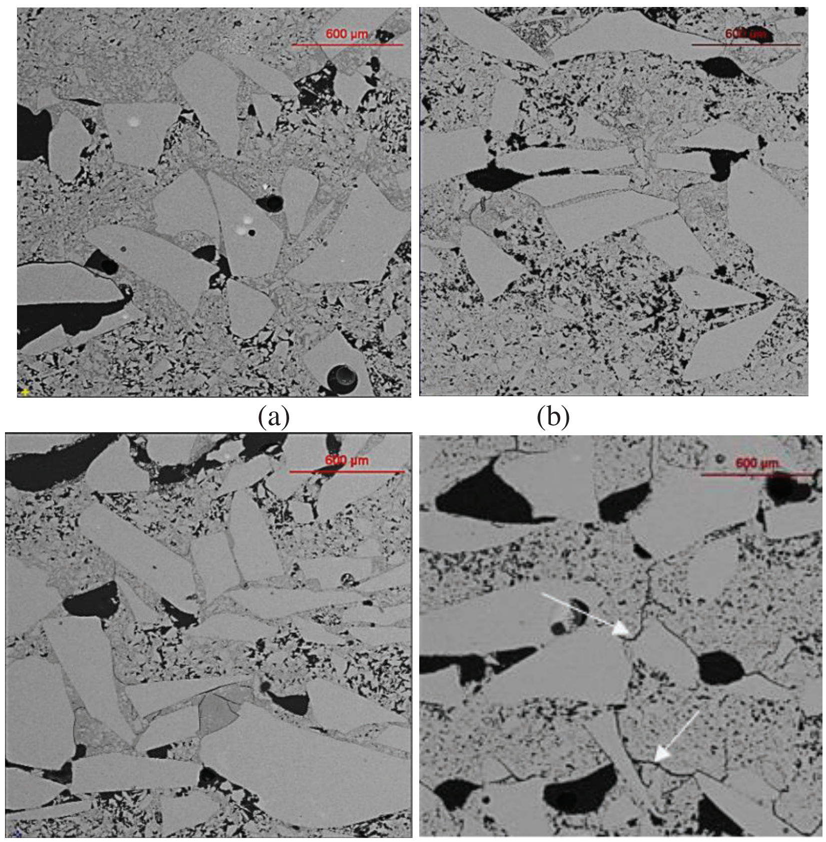
In the differential laser flash calorimetry method, a reference specimen (subscript "R") and the test specimen (subscript "M"), are mounted together under the same condition at the same temperature and irradiated uniformly with homogenized laser beam. The temperature rise (ΔT) of the reference (graphite) with known specific heat capacity (C_p) and the temperature rise of the test specimen are both measured with non-contact infrared radiation thermometer. If the density (ρ) and thickness (L) are known, then the specific heat capacity of the specimen can be calculated (Eqn.1):

$$\left(\rho c_p\right)_M = \frac{L_R \Delta T_R}{L_M \Delta T_M}\left(\rho c_p\right)_R \qquad \text{Eqn. 1}$$

Due to the abrupt temperature rise resulted by the phase transformation, it will cause an overestimate of the temperature rise in Equation 1. Consequently, a decreased heat capacity value is calculated at 1200°C (2192°F). This exothermic phase transformation effect correlates to the laser flash measurements (Figure 3a) very well.

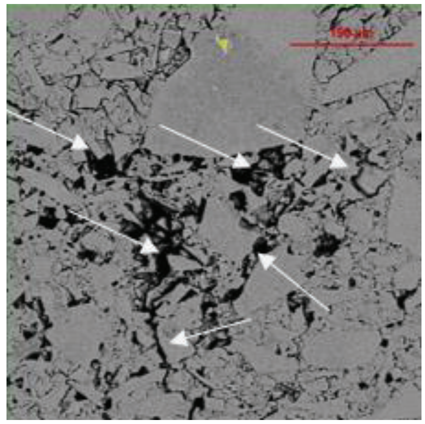
EFFECT OF FIRING TEMPERATURE ON MECHANICAL PROPERTIES

A relatively higher firing temperature within the range studied,850°C (1562°F) and 1000°C (1832°F), provides more significant sintering and as a result, the MoR of the shell increases. However, as shown in Figure 4, when firing shells at an even higher temperature of 1200°C (2192°F), the MoR of the shell significantly decreases. According to the DTA results shown in Figure 5b, the devitrification range for amorphous silica starts at 1020°C (1868°F). When firing the shells at 1000°C (1832°F), the sintering effect is still predominate on increasing the shell strength. However, when increasing the firing temperature to 1200°C (2192°F), a significant amount of cristobalite was formed in the shell. During cooling, the volume change of cristobalite, as it passes through the low-temperature inversion range, is reported to be 7%[35]. These volume changes could result more micro-cracking, weakening the structure (Figure 9).



(a) (b)

(c) (d)



(e)

Figure 9. Microstructure of silica shells after being fired at different temperatures: green (a), 600°C (1112°F) (b), 850°C (1562°F) (c), 1000°C (1832°F) (d), 1200°C (2192°F) (e) showing that a high firing temperature of 1200°C (2192°F) causes more micro-cracking when the shells are cooled down due to the difference in volume change resulted by devitrification

Moreover, a higher firing temperature results in more coarsening, thus larger grain sizes are expected in the bond phase of a shell fired at 1200°C (2192°F). Spontaneous cracking occurs predominately in large-grained samples because the reduction in the internal strain energy is proportional to the cube of the particle size whereas the increased surface energy caused by the fracture is proportional to the square of the particle size[36]. These energy differentials or differences mean that large-grain samples above a critical size are weak and in general have poor physical properties because of the substantial grain/matrix interface stresses. Consequently grain coarsening in the bond phase may contribute to the crack propagation.

APPLICATION

This research initiated quantitative study of amorphous silica devitrification in investment shells. More firing profiles need to be studied to complete this work. However, based on the current results, one can see that the firing profiles significantly affects the thermos-physical properties of the shells. In an investment foundry, the cristobalite formation should be maximized during the pouring process to aid shell knock-out process.

Therefore, if the preheating is integrated with the firing process as one step, a higher firing/preheating temperature (greater than 1000°C) should be used. It is noted that the shells needs to be kept at above 300°C before the hot metal is poured. This is to avoid the β to α transformation where micro cracking forms and weakens the shell.

However, if an investment foundry utilize a two-step heating before the final pour, i.e. firing-inspection-preheating, then a lower firing temperature (600°C) and a higher preheating temperature (1200°C) is preferred regarding to maximize the cristobalite formation during pouring. It is important to keep in mind that if one choose a lower firing temperature, additional layer of shell may be required to reach minimum shell strength.

The aluminum investment foundry will especially benefit from this research. Typically, the firing or preheating or pouring temperature in the aluminum investment foundry don't exceed the silica devitrification temperature. Therefore one can't take the advantages of cristobalite formation to aid the shell knock-out process. By utilizing suggested practices above, the shell knock-out process should be improved.

CONCLUSIONS AND FUTURE WORK

Colloidal silica binder was found to be the most active component within the ceramic shells with respect to devitrification during the multiple heating/cooling stages of investment casting processes. In this article, the effect of firing temperature on devitrification behavior of silica based shell molds was correlated with changes in thermal and mechanical properties.

Devitrification temperature range for this particular colloidal silica binder was found to start at around 1000°C (1832°F) at the heating rate of 15°C/min (27°F/min). For firing temperatures below 1000°C (1832°F), a higher firing temperature reduces the reactivity of the colloidal silica binder toward devitrification by decreasing specific surface area, resulting in less cristobalite formation upon reheating before mold pouring. The degree of devitrification affects the thermal conductivity of the shell molds. The excess heat generated from devitrification during the laser flash tests causes an underestimate of the heat capacity at 1200°C (2192°F).
Moreover, at below 1000°C (1832°F), increasing the firing temperature provides up to 40% more strength to the shell, whereas an even higher firing temperature (for example, 1200°C or 2192°F) decreases the shell strength by over 50% compared to the green shell.

It is noted that the firing time (one hour) used in this study is shorter than what a typical investment foundry uses. Therefore, the amount of devitrification which actually takes place may be much greater than the results presented in the paper. That will certainly magnify the effect of firing temperature on the thermo-physical properties. A proposal quantifying the kinetics of silica transformation at longer time has been approved by AFS 4L committee and AFS research board.

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INVESTMENT CASTING INSTITUTE

Economical Engineered Powder Blends for Precision Investment Casting Backup Slurries – “How Its Made”

Scot Graddick
Imerys Refractory Minerals

634TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 7

Economical Engineered Powder Blends for Precision Investment Casting Backup Slurries

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1.0 ABSTRACT

Broad particle size distribution, monomineralic blends, for PIC backup slurries, have become very popular in recent years. To date, these have been centered mostly around fused silica-based formulations. Much of this work has been geared toward producing smaller parts (turbocharger wheels, etc.), where precise tolerances are required. Imerys has developed a line of Hybrid products that have very unique properties, when compared to fused silica-based systems. These Hybrid products are a blend of aluminosilicate + fused silica, which allows them to associate some of the key attributes/benefits of both systems, and by definition, would generally make them more economical. Hot creep/deformation resistance of the Hybrid products is better than for fused silica-based systems, while still maintaining a similar thermal expansion profile to fused silica-based systems. Also, knockout/cold MOR for the Hybrid systems is in line with that of FS-based systems, even though, comparatively speaking, a great deal less cristobalite is formed in the Hybrid systems, during and after casting. In terms of shell build, the Hybrid products are quite outstanding, when compared to "conventional particle size distribution" systems.

In conjunction with Aristo Cast, IRM ran a trial of Hybrid+ versus a relatively thin, virtually 100% fused silica, conventional shell system. Information regarding comparative shell build, fired crystalline silica content, shell strength, knockout, and finished product tolerances will be discussed.

2.0 BACKGROUND

As a world-wide producer of refractory raw materials, selling to diverse industries throughout the world, Imerys Refractory Minerals personnel often find ourselves trying to be "all things to all customers." That is, we are often called upon to solve some rather significant problems, with our product portfolio. The Investment Casting industry is currently facing a number of technical and economic challenges. In order to maintain and improve its competitive advantage versus other metal-forming technologies, the new moulding solutions have to enhance the productivity of the process, maintain the highest possible dimensional accuracy, and allow the greatest flexibility, in terms of type of alloy, casting temperature, and operating conditions. Our team knew that our ability to find technical solutions to serve these requirements, without impacting the overall cost of the process, would have to depend upon two things: 1) finding some way to reduce number of shell layers/increase throughput through the shell room, and 2) including something to help with knockout. Part two was easy, as most folks in the industry know the effect of fused silica, when it comes to knockout. But- we knew it couldn't be a 100% fused silica system, due to cost/price (even though dimensional accuracy of systems containing a high amount of amorphous phase is without question). We also knew that, by using a broad distribution material, we might be able to build shell faster than with standard IC sizes. It also occurred to us that we had to find some sort of economical rheology modifier, compatible with the mineralogy and chemistry of our blend, to help "thicken' the slurry, without permeability becoming a real issue.

3.0 CONCEPT

This is certainly a bit of an overgeneralization, but it is safe to say that most of Europe and Asia are using aluminosilicates for slurry and stuccos in PIC backup shell systems. This works quite well for many casters, but this practice does come with a few issues. Shell based on predominantly aluminosilicates, especially certain lower duty/purity chamottes, can become quite hard/sintered after casting, making shell removal quite difficult, at times. This is mainly due to lower alumina content, associated to ferric oxide, titania, and alkali/alkali earth oxides present in the aluminosilicates being used. The first thing we normally suggest to aluminosilicate customers having shell removal problems is the possibility of switching to one of Imerys' aluminosilicates from our Mulcoa plant. Imerys Refractory Minerals-US is quite blessed to have our production plants located close to the lowest ferric oxide and alkali/alkali earth oxide-containing raw materials available on the planet. Because of this, Mulcoa's products will not sinter as much (during/after casting) as many of the other aluminosilicates commonly used in the PIC market today.

If knockout is still an issue, we then suggest adding fused silica to the backup system. The addition of fused silica to an aluminosilicate-based backup system can dramatically affect the knockout properties of the shell. This is due to transformation of fused silica to beta-cristobalite, at higher casting temperatures, and then the subsequent transformation of that beta-cristobalite to alpha cristobalite, as the shell cools to room temperature. This transformation is quite displacive/disruptive/weakens the shell, and, thus, helps a great deal with shell removal.

Using one of Mulcoa plant's aluminosilicates in the flour portion of our potential mix made perfect sense. But, we also knew that knockout was one of/if not the main concern for many potential customers. So, we decided that blending our aluminosilicate with a healthy dose of fused silica made the most sense. Coming up with a broad distribution mix based on this two component system was, of course, not difficult…which we did (by blending fine stucco with a coarser flour and a finer flour, in the most appropriate ratios). This Imerys mix is now known as Hybrid. It certainly helped build thickness, but not to the degree that we were hoping for. In searching through some of the different, available "co-products," from other Imerys plants, from around the world, we found the perfect (and now patented, for this application) material to use as a rheology modifier for Hybrid. Thus, Imerys' Hybrid+ was "born," as this material exhibits outstanding shell thickness building/draining properties (especially when compared to Imerys' Hybrid product).

4.0 NORTH AMERICAN MARKET DISCUSSION

For some of our European and Asian customers, we knew that we had a product that could help them with shell room throughput and knockout. There is currently strong interest in Hybrid+ in the Japanese market. But, for the North American market, these weren't exactly new concepts- more fused silica is used in the North American PIC market than anywhere else in the world, with broad distribution backup slurry mixes making up a significant percentage of that usage, these days. But, while testing Hybrid+ in earnest, we did find some very real benefits, versus broad distribution backup slurries based on virtually 100% fused silica.

There can be some "issues" encountered, when using a large percentage of fused silica in PIC shells. Generally speaking, the green strength of fused silica-based backup systems is somewhat less than that of aluminosilicate-based systems. This can result in cracking, etc., during dewaxing. Also, the creep/hot deformation of shells based on fused silica can, at times, be lower than desired. Of course, I am not saying that 100% fused silica systems can't be/aren't successful, as we know that they are/can be quite successful. In fact, we produce some of these materials, and they have been gaining in popularity, over the last few years. But- we have found that the addition of a specific amount of Mulcoa's aluminosilicate material, to a fused silica-based system, definitely helps with the green strength and hot strength/creep resistance of these systems. Figure 1 shows our hot deformation test results, when comparing Hybrid+ versus fused silica (and chamotte) backup systems. Obviously, Hybrid+ dramatically outperforms both materials.

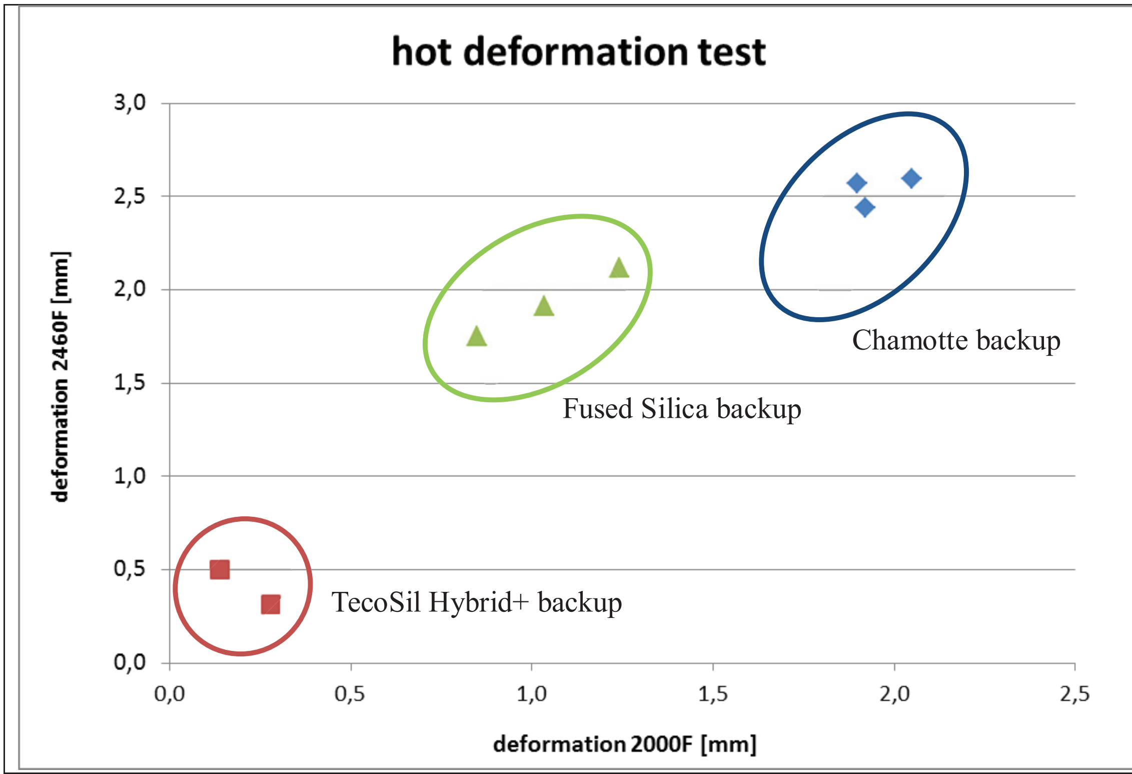


Fig. 1 Hot deformation behaviour of various shell systems.

Obviously, we keenly understand the fact that many US casters are using a predominantly fused silica-based shell in order to achieve certain, very tight, dimensional tolerances on cast parts. This is especially the case for the production of turbochargers. Because most aluminosilicates (besides Imerys' 60% alumina aluminosilicate calcine and Imerys' UK-produced aluminosilicate calcine) have a somewhat higher coefficient of thermal expansion than fused silica, once would assume that using a blend of the two materials could affect the overall thermal expansion of the system in question. But, what we have found is that the expansion of the stucco material more greatly impacts the overall shell thermal expansion properties, when compared to the expansion properties of just the slurry material, itself. The thermal expansion properties of Hybrid+ are quite acceptable (similar), when compared to those of fused silica-based backup systems (especially in conjunction with fused silica stuccoes).

Tab. 1 Slurry properties of different flours.

		TS 200F	TS broad PSD	Hybrid+
filler load	**wt.-%**	**66**	**69**	**72**
viscosity	sec [Z5]	11	11	11
slurry density	g/ccm	1.65	1.80	1.95

Shell build/layer thickness for Hybrid+ is nothing short of outstanding. Obviously, shell building efficiency is a major factor in shell room throughput, and one of the main reasons for the success of broad distribution slurries in the PIC market today. The particle size distribution of Hybrid+ is quite unique in that tightly controlled particle packing helps build shell thickness without affecting permeability of the shell too badly (which can cause non-fill issues). This is achieved by using powders (in the formulation) that have very unique particle size distributions, produced using carefully controlled milling of very particularly-sized feedstock. The patented material we use as a rheology modifier definitely helps thicken/enhance the plasticity and viscosity of the slurry, while still allowing for excellent draining properties. At viscosities comparable to standard backup slurries, the filler load is quite a bit higher for Hybrid+ (see **Tab. 1**). Looking at a cross section of shell produced using Hybrid+, it is quite easy to see a very healthy shell structure (see **Fig. 2**), as well as the thickness differences between slurries based on Hybrid+ and standard fused silica.

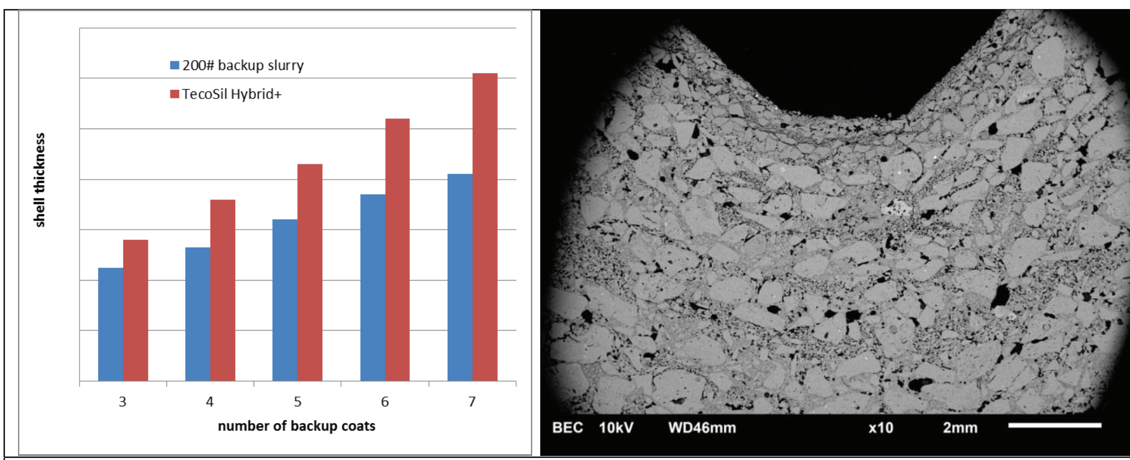


Fig. 2 Shell building properties (left) and shell structure (right) of Hybrid+

5.0 CRYSTALLINE SILICA DISCUSSION

Obviously, a "hot" issue in the foundry industry these days revolves around new regulations pertaining to potential crystalline silica dust issues. One thing is for certain- after casting a fused silica shell at iron melting temperatures (and above), the shell is definitely going to devitrify to predominantly cristobalite. As mentioned before, that is one of the really good things about fused silica (in terms of shell knockout). Having said that, anything that leads to reduced crystalline silica in a shell is probably a good thing, these days, if it still works! Obviously, with less fused silica from the start, Hybrid+ is guaranteed to generate less cristobalite in the fired shell. But, the addition of aluminosilicate to a fused silica-based system also helps to retard the devitrification of the fused silica (present) into cristobalite, without dramatically affecting the knockout properties of the system. This is an outstanding attribute of Hybrid+.

6.0 ARISTO CAST TRIAL

The good folks at Aristo Cast, based in Almont, Michigan, agreed to run a trial on our Hybrid+ product. Without divulging too much detailed information regarding what Aristo Cast is doing- Aristo Cast generally uses a 100% fused silica-based shell, based on traditional fused silica investment casting sizes. To us, their shell seemed quite thin. Generally speaking, their typical shell is composed of a face coat/stucco, with 3 backup layers and a seal dip; Imerys' fused silica is normally used in production. Aristo Cast personnel notified us ahead of time that they intended on building the slurry themselves, as normal, and before we arrived, which was fine with us (as we wanted this trial to be as "seamless" as possible). We just advised, ahead of time, that they should try to keep slurry viscosity at around 12 seconds in a #5 Zahn cup. The normal number of layers would be used in the Hybrid+ containing shells- Aristo Cast's normal prime coat/stucco, three Hybrid+/stucco layers and a Hybrid+ seal dip. While building the slurry, Aristo Cast personnel discovered that Hybrid+ containing slurry is **very** different than slurry based on standard fused silica IC sizes, in terms of solids content, viscosity, shearing, etc. There is a definite learning curve with this material.

Still, upon arrival, Aristo Cast already had several Hybrid+ shells being autoclaved. It was easy to see the very nice surface finish on the shells containing Hybrid +. All of the shells made it through the autoclave with no problem, at all, even though it was quite evident that these shells were somewhat thicker than Aristo Cast's normal FS shell (**Fig. 3**). Obviously, this was very good news, as permeability was certainly in question (versus their normal, thinner shell). The density of the Imerys aluminosilicate used is a bit higher than that of fused silica (2.60 g/cc versus 2.17 g/cc). The trees in question consisted of medium-sized parts, and the trees were not abnormally large. On average, the trees containing Hybrid+ weighed about 5 lbs more than the trees based solely on FS. Some of this could be based on material density (Mulcoa's products versus fused silica), but this was, quite obviously, mostly due to shell thickness. We didn't view this as a problem, though….this was an obvious opportunity for Aristo Cast to try removing some layers from their shell/potentially help their shell room throughput.

Fig. 3 Left: Aristo Cast standard shell, right: Hybrid+ shell. Both trees were built with one primary, three backups and a seal coat. Note the much thicker shell in case of using Hybrid+.

Upon examining the leftover slurry, we found that quite a bit of evaporation had occurred and that the slurry was quite thick. Our viscosity test results differed some from Aristo Cast personnel's results, but, with Buntrock personnel's help, we all settled on where the viscosity needed to be (and adjusted it accordingly). The Hybrid+ based slurry certainly exhibited exceptional draining characteristics- another real "plus" for this material.

After pouring metal into these initial shells, we did notice a very minor amount of non-fill at the tops of a few of the trees. We attributed this to the slurry possibly being a bit thicker than originally desired during coating. Still, most of the castings looked quite good. At the knockout station, there wasn't a very noticeable difference between the knockout of the Hybrid+ containing shell, and Aristo Cast's normal FS-based shell. In fact, at times, the Hybrid+ containing shell appeared to be a bit better, in terms of knockout. Shell samples were taken for testing at Imerys' test facility in Villach, Austria. As expected, we found significantly less crystalline silica in the Hybrid+ containing shell. The standard fused silica shell transforms 47 wt.-% of its fused silica into cristobalite at fast cooling outside parts and up to 76 wt.-% at slow cooling areas close to the runner. In contrast, the devitrification rate in the Hybrid+ shell is below 20 wt.-%, even at the hottest parts of the shell (Fig. 4).

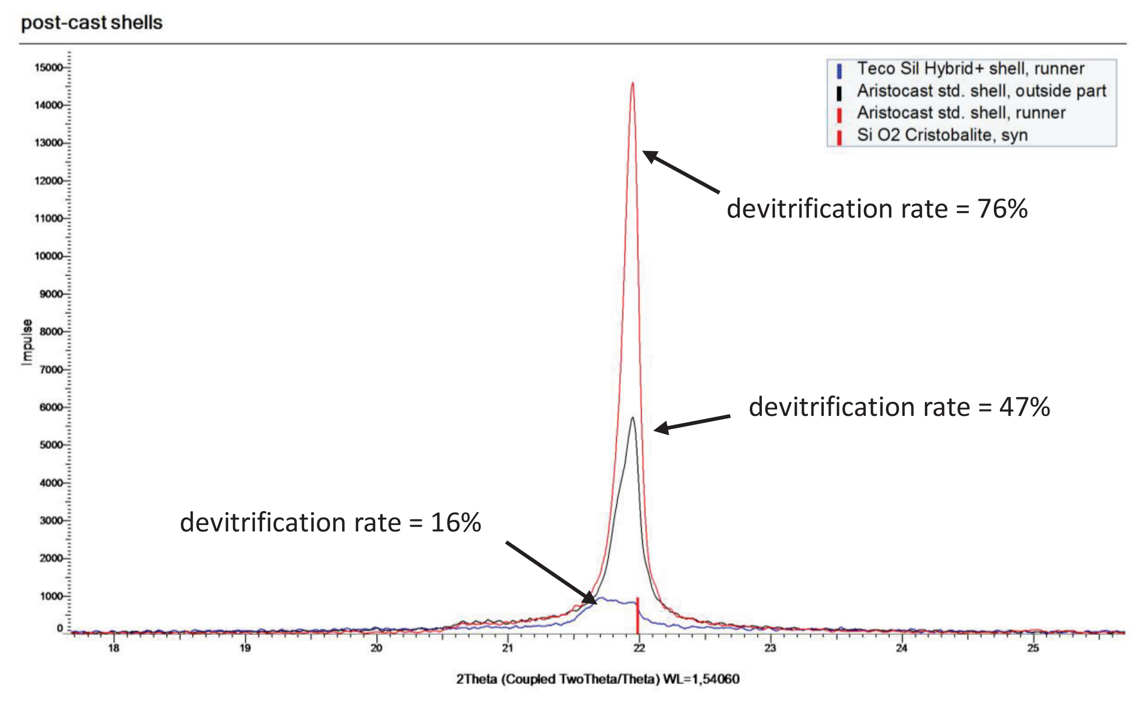


Fig. 4 XRD pattern of post-cast shell samples, main peak of cristobalite is shown.

For good reason, the folks at Aristo Cast have always been very proud of their plant and their processes. During previous trials, Aristo Cast personnel never made any bones about the fact that they saw very little chance of them changing their process (to switch to something new being "trial-ed" there). But- with Hybrid+, we could tell that those folks could clearly see the opportunity to potentially help throughput in their shell room. Even though their normal shell is composed of just a few layers, they could see that, with Hybrid +, the potential still exists for them to remove one or two layers from their shell. This was mainly due to the obvious thickness of the shell, but also due to the green and pre-fired/cast strength of the trees containing Hybrid+. Buntrock personnel were kind enough to test dipped wax bars for green strength, hot strength, and fired strength, with the results being as follows:

Tab. 2 Results of mechanical testing and permeability measurements.

			Std. shell	Hybrid+ shell
Green	MOR	psi	407	825
	thickness	in	0.202	0.245
	load	lbs	6.91	21.25
Hot/Wet	MOR	psi	212	414
	thickness	in	0.208	0.244
	load	lbs	3.81	10.26
Hot 1800F/2hr	MOR	psi	1066	1616
	thickness	in	0.203	0.229

	load	lbs	7.29	14.47
Fired 1800F	MOR	psi	270	805
	thickness	in	0.2	0.227
	load	lbs	4.54	17.51
Hot 1950F/2hr	MOR	psi	1234	1722
	thickness	in	0.208	0.215
	load	lbs	8.69	13.37
Fired 1950F	MOR	psi	222	842
	thickness	in	0.211	0.228
	load	lbs	4.04	18.57
permeability	green	cD	no result, as ceramic stuck to the wax	
	fired 1600F	cD	19.7	2.3

Obviously, the Hybrid+ containing shell was thicker and stronger across the board, allowing for the potential of a foundry dropping at least one coat, when using this material. Fired shell strengths did not truly coincide with what was seen visually, and in actuality, in terms of knockout. Shell knockout for the Hybrid+ containing shell was, again, actually quite good/comparable to that of the standard FS-based shell.

There was a tremendous permeability difference, but we knew this would be the case. Such a thin shell, produced using very standard IC FS powders, would be quite permeable, compared to a slurry designed to build shell thickness. The better comparison here would be against a broad distribution, FS-based slurry, that was designed to help build shell thickness. Obviously, due to the extremely minor non-fill issue (from the initial pours), the thickness of the slurry, the very thick shell (compared to normal) and the permeability results, we forged ahead with dipping some shells with even fewer coats. While we were still at the foundry, Aristo Cast personnel produced shells with one and two less backup layers. As thin as their normal shell system is, I had very little hope for the shell with just three layers. But, the subsequent report from Aristo Cast's GM was as follows:

We cast the shells that were processed with 1 & 2 less coats than our standard process. Both made it through the autoclave with no issues. The one with one less coat held in casting and the parts look good. The one with 2 less coats leaked about 5 seconds after we filled the mold. I think with a little effort we stand a very good chance of eliminating 2 coats. As soon as time permits we'll give it a shot.

Fig. 5 Castings after shake out. Tree in the front: Hybrid+ shell, trees in the back: std. shell.

We were quite pleased with their comments. Aristo Cast is certainly using a FS shell in order to meet some very exacting/tight tolerances on many of the parts they are producing. Aristo Cast personnel did not notice any difference in terms of dimensional properties, when comparing the two different shell systems. Obviously, this can be related back to what we mentioned earlier, re: the stucco affecting dimensional attributes of the shell, more than the slurry. Without question, this trial was a huge success!

7.0 CONCLUSION

Imerys set out to produce an economical back up slurry material- one that can help the efficiency of a foundry, but not only through reducing coats...but also by incorportating lower cost, but highly effective, raw materials into the formulation. We needed this backup slurry material to exhibit good knockout, while maintaining the ability to help with extremely accurate dimensional control. Doing all of this, while at the same time reducing overall crystalline silica content in fired shell (for environmental, health, and safety issues) makes Hybrid+ a product that has real long term potential in the PIC industry. Please contact one of our three fine distributors to the investment casting industry in North America (Buntrock, Ransom & Randolph, and Remet) or your Imerys representative, for further information regarding TECO-Sil Hybrid+.

INVESTMENT CASTING INSTITUTE

Optimizing the Tetrashell Build Structure to Reduce Shell Cracking in the Autoclave with SLA Patterns

Kevin Zaras
DSM Somos

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 8

Optimizing the Tetrashell Build Structure to Reduce Shell Cracking in the Autoclave with SLA Patterns

Tom Mueller, Mueller AMS
Kevin Zaras, DSM

Background

From the first introduction of additive manufacturing in the late 1980's, there was a great deal of interest in being able to create prototype patterns for investment casting. The ability to print prototype patterns would allow prototype castings to be created without the cost and lead time associated with creating wax pattern tooling.

Early trials with stereolithography (SL) patterns had very limited success. Thermal expansion of the solid pattern tended to crack and fracture shells in the autoclave, rendering the shell useless. PCC personnel stated that even with additional coats on the shell, success rates were in the 20% range. Five patterns would be processed in hopes of obtaining one prototype casting.

In 1992, 3D Systems developed the QuickCast build style, which hollowed the pattern and used an internal support structure to hold the walls of the pattern in place and keep them from flexing. Initial versions used square and triangular support structures, but eventually a hexagonal support structure was adopted. The hollow build style was thought to provide two advantages. First, it significantly reduced the resin mass that must be burned out of the shell, thus reducing both burn out times and residual ash. Second, and more importantly, because it was hollow, the pattern could collapse inwardly as it expanded with heat, reducing the pressure exerted on the shell and reducing the likelihood that the shell would crack in the autoclave. While the incidence of shell cracking was reduced significantly, shell cracking continued to be the major cause of failure of SL patterns in investment casting.

Another hollow build structure called Tetrashell, was developed at the Milwaukee School of Engineering as an alternative to the hexagonal internal structure. A change in the internal structure suggested it may have the potential of reducing the incidence of shell cracking. This investigation was initiated to evaluate the shell cracking tendency of the Tetrashell structure relative to the QuickCast structure.

The QuickCast Structure

The QuickCast build style appears to be a hexagonal cell structure when viewed from the top. However, only two sides of the hexagon are created at any one time. Opposite sides of the hexagon are built for several layers until a short wall is built. Then the build shifts and another pair of opposite sides are built until the height of the cell wall is reached. Finally the third set of walls are built completing the hexagon. The process is repeated until the pattern is completed. Figure 1 shows the internal structure. Note that the completed support structure is very open and allows fluid to drain throughout out the structure. An open structure is important. If closed cells were used, uncured resin would be trapped inside the pattern and would be solidified in the post cure process.

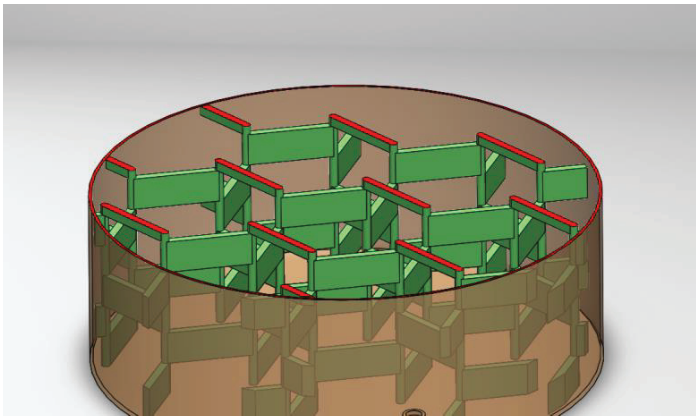


Figure 1. QuickCast internal structure.

One disadvantage of this structure, however, is that the structure creates a post at every corner of the hex that runs from skin to skin. That post, illustrated in Figure 2, is supported over its entire length by the short walls that create the hexes. With the reinforcement provided by those short wall sections, it is virtually impossible for the post to buckle. The pattern is built hollow so that it can collapse inwardly as it expands with heat. However, the reinforced posts at each corner of the hex effectively prevent the pattern from collapsing. Consequently, the

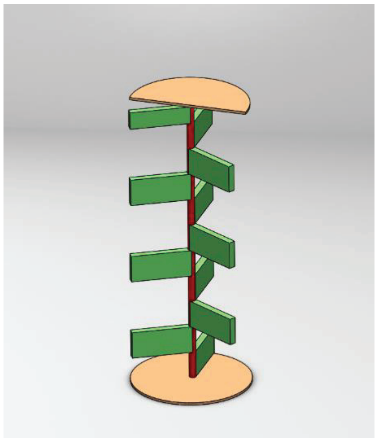


Figure 2. Post at the corner of the hexagonal support structure.

pattern expands nearly as much as if it were a solid pattern and in spite of being hollow, thermal expansion of the pattern is likely to crack the shell.

A work around was developed to minimize the chances of shell cracking. If the pattern was vented, and the skin of the pattern was punctured, steam could enter the interior of the pattern as soon as the autoclave was pressurized. The steam quickly heats the internal structure and it softens to the stiffness of a gummi bear. With that softness, now the rod can buckle and the pattern can collapse inwardly as intended.

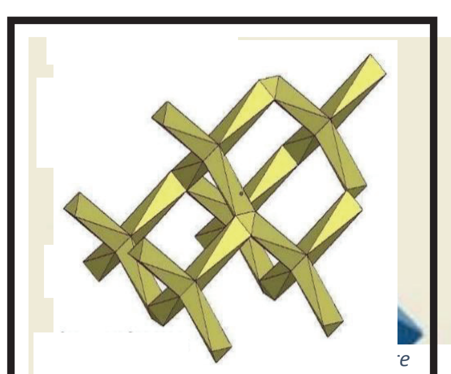
This process is used by nearly all foundries who use QuickCast patterns to minimize the chances of failure in the casting process. While it works very well, it adds quite a bit of effort, cost and time to the casting process:

1. To make it through the autoclave, at least one vent must be added to each pattern. Patterns larger than 6 inches or so will require multiple vents. Vents can be created with a piece of spaghetti wax, or a more complex molded vent can be used. The vent must be attached to pattern during assembly. In most cases, a hole through the skin is drilled prior to placing the vent and the vent covers the hole. The pattern is then shelled normally.
2. After the shell is complete, the vent must be opened so that there is a pathway to the interior of the pattern for steam to enter.
3. After the autoclave process, the pattern is burned out. After burnout, the shell is cooled to clean out any ash and to patch the vents. Vents must be patched to prevent molten metal from leaking out during pouring.
4. After the casting has cooled, the vent stubs must be ground flat.

All these additional steps add cost and time to the casting process. Most importantly, they add labor to the casting process.

The Tetrashell Structure

Like QuickCast patterns, Tetrashell patterns are also hollow with an internal support structure.



However, the internal structure is very different. The basic unit of the support structure is a "V" made of two legs. A second "V" is inverted, rotated 90 degrees, and joined to the first as shown in Figure 3. This 2-V basic structure is repeated to create the internal structure. Figure 4 shows several basic units connected to form the internal support structure. Like QuickCast, It is a very open structure and will allow drainage from all points of the pattern. However, unlike QuickCast, there are no posts running from skin to skin. This should allow the pattern to collapse internally much more easily than QuickCast patterns.

Figure 4. Internal structure of a Tetrashell build style.

Force Exerted on the Shell from Thermal Expansion

The pressure exerted on the shell by the pattern as a result of thermal expansion is given by

$$P = k * CTE*(T_2-T_1)*h$$

Where P= *pressure exerted*

k = *stiffness of the structure per square inch*

CTE = *coefficient of thermal expansion*

T_2 = *Temperature of the autoclave*

T_1 = *ambient temperature*

h = *the thickness of the pattern*

To illustrate, consider Figure 5. In view a, a part is at ambient temperature T_1. In view b, the temperature has been raised to T_2 and the part has expanded. That expansion is equal to the CTE times the increase in

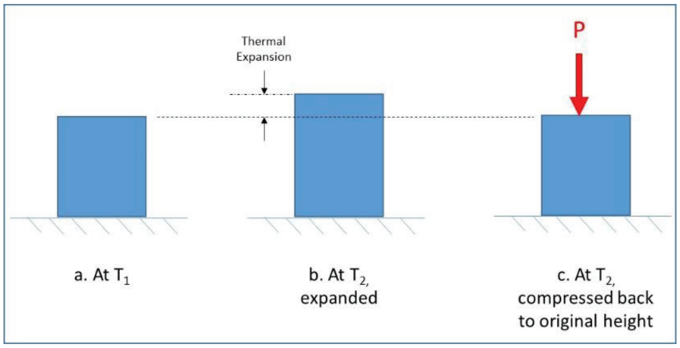


Figure 5. Illustration of the formula for pressure exerted on the shell.

temperature. In view c, an external force has been exerted on the top of the part to compress it back to its height at T_1. This is the force that would be exerted on the shell over the same temperature rise.

The CTE is published for most SLA resins and the ambient and autoclave temperatures are similar for nearly all foundries. What is not known is the stiffness of QuickCast and Tetrashell structures. Once the stiffness, is known, the pressure exerted on the shell can be calculated. The next step is to determine the stiffness.

Test Plan

To determine the stiffness of the internal structures, test specimens were created as shown in Figure 6. All specimens were a flat disk 0.28" thick and 2.2" in diameter. The smaller height section around the circumference was ground off after the part was built. It was removed to provide a break in the outer wall so that the stiffness of the outer wall would not influence the measured stiffness of the pattern.

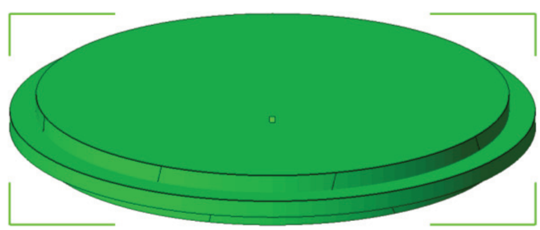


Figure 6. Test specimen

Both QuickCast and Tetrashell provide some user control over the density of the support structure. In QuickCast, you can control the size of the hatch and the height of the short walls that make up the sides of the hex. In Tetrashell, you can control the thickness of the leg and the length of the leg. The values selected for these build parameters significantly influence the stiffness of the structure created.

For the test, both QuickCast and Tetrashell specimens were created using a range of build parameters. All specimens were built using the DSM Element resin to ensure that differences in resin properties did not influence the measured stiffness.

Nine QuickCast specimens were built, three each with 0.100", 0.175" and 0.25" hatch spacings.

Thirteen Tetrashell specimens were built with six different combinations of build parameters. They included the following:

Leg Length (in)	Leg Diameter (in)	No. of Specimens
0.162	0.025	3
0.162	0.030	4
0.217	0.025	3
0.217	0.030	1
.0325	0.025	1
.0325	0.030	1

The center outer ring was trimmed off on each specimen to eliminate the influence of the circumferential wall.

The stiffness of each sample was then measured in a tensile/compression test machine. Figure 7 shows one of the Tetrashell specimens mounted in the test machine.

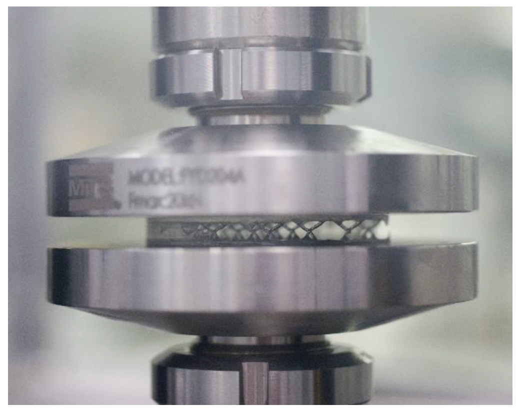


Figure 7. Specimen mounted in compression tester.

The test machine gradually increased the compressive force until a specified displacement was reached. The maximum force and displacement were recorded. Dividing the force by the displacement provided the stiffness of the sample. Dividing that stiffness by the area of the specimen yielded the stiffness per square inch of pattern. The stiffness obtained for multiple specimens were averaged to obtain the result.

Of course, that number will vary with the thickness of the specimen. All specimens were built to the same thickness so comparisons between specimens can be made.

Since all specimens were made from the same material, the amount of thermal expansion would be the same. The temperature in the autoclave rises approximately 175F (75F to 250F). The CTE of the Element resin is 76.1E-6 in/in/F and the thickness of the specimen was 0.28 inches. Consequently, the thermal expansion is 0.003729 inches.

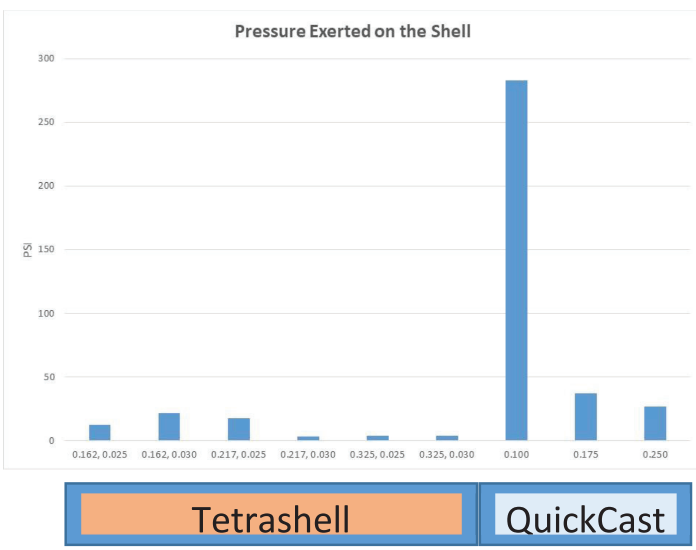
The measured stiffness is then multiplied by the thermal expansion to obtain the pressure exerted on the shell.

Results

The results are detailed in the following table.

Type	Parameters	k, (lb/in/in^2)	CTE	T_2-T_1, °F	Expansion	Press. (lb/in^2)
Tetra Shell	0.162, 0.025	3,399.4	76.1	175	0.0037289	12.68
Tetra Shell	0.162, 0.030	5,821.2	76.1	175	0.0037289	21.71
Tetra Shell	0.217, 0.025	4,756.2	76.1	175	0.0037289	17.74
Tetra Shell	0.217, 0.030	895.2	76.1	175	0.0037289	3.34
Tetra Shell	0.325, 0.025	991.1	76.1	175	0.0037289	3.70
Tetra Shell	0.325, 0.030	1,130.6	76.1	175	0.0037289	4.22
QuickCast	0.100	75,819.0	76.1	175	0.0037289	282.72
QuickCast	0.175	9,912.9	76.1	175	0.0037289	36.96
QuickCast	0.250	7,205.6	76.1	175	0.0037289	26.87

The results are also shown graphically in the column chart below.



Summary of Results

1. Pressure exerted on the shell by QuckCast patterns ranged from 26 to 282 psi. The tighter the hatch spacing, the greater was the pressure exerted.
2. Pressure exerted on the shell by Tetrashell patterns ranged from 4 to 22 psi. The higher pressures were observed with shorter leg lengths.

3. A QuickCast pattern with hatch spacing of 0.100 will exert 84 times as much pressure as a Tetrashell pattern with 0.217 in leg length and a 0.025 inch leg diameter.

Conclusions

1. Moving to a Tetrashell buld style from a QuickCast build style will significantly reduce the likelihood of shell cracking in the autoclave.
2. Patterns built using the Tetrashell build style will likely not require the multiple vents typically required on QuickCast patterns to prevent cracking in the autoclave, eliminating assembly labor, vent patch labor, and vent stub grinding labor.

Follow-On Work

In the next few months, these results will be confirmed in actual autoclave tests.

Acknowledgements

The authors would like to acknowledge the contributions of Peridot, Inc. who contributed many of the test specimens used in testing.

INVESTMENT CASTING INSTITUTE

Improved Consistency of Slurry and Shell Properties Using Particle Size Control of Ceramic Flours

Tom Branscomb
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64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 9

Improved Consistency of Slurry and Shell Properties using Particle Size Control of Ceramic Flours

Tom Branscomb, Buntrock Industries

Abstract

Particle size distribution changes of ceramic flour can affect slurry properties including slurry density, rheology, and coating thickness. Shell properties that can be affected are permeability, thickness, edge coverage, and strength. For critical applications like Titanium and DS/SC casting, control of particle size can mean the difference between success and failure. Methods and examples are presented on how to improve particle size control.

Introduction

It has been common for operators in the shell dipping room to experience some slurries that are more difficult to drain than others. In most shell rooms there were one or two operators, usually with years of experience, that could be counted on to use their skills to apply good coatings even if the slurry had draining problems. This variability from slurry to slurry was most notable in the critical prime slurries but is certainly not limited to those slurries. All slurries experienced similar variation.

The use of robots rather than experienced operators to apply prime coatings to wax assemblies requires that this variability is reduced or eliminated. The robots, at least for now, cannot adapt to unexpected differences from slurry to slurry. The source of variability can be from any of the materials in the slurry as well as from the changes in the slurry as it is being used. Since the refractory powder loading for prime slurry is about 80% by weight and is the largest single component of the slurry, this paper is focused on investigating the refractory powder and what can be done to reduce slurry variability resulting from the powder. The purpose of the paper is to show how particle size of the refractory can have large effects on slurry properties and thus on casting quality.

Experimental Work

For this work, Tabular Alumina was chosen as the material to investigate. This is a material that is commonly used to make prime slurries for Super Alloy Equiaxed, Directionally Solidified, and Single Crystal castings. To make slurries, I started with Shellbond 107 binder, a polymer enhanced colloidal silica binder available from Buntrock Industries. Equal parts of commercially available 200 and 325 mesh Tabular Alumina were added to the binder. Antifoam and surfactant were also used as necessary. Particle size distribution and surface area of the two powders were measured at the Buntrock Lab. See Figure 1.

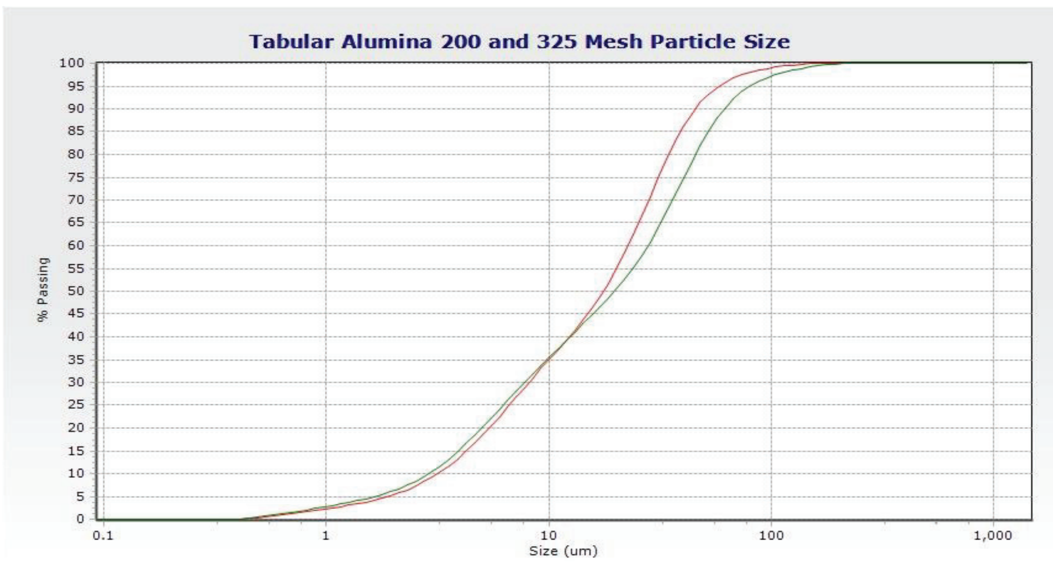

Figure 1. Particle size of Tabular Alumina used to make slurry. (Red line is 325 mesh.)

Surface Area: 200 mesh Tabular Alumina = 0.95 sq m/gm
325 mesh Tabular Alumina = 0.94 sq m/gm

Note that there is little difference at the finer end of the particle size curves for the two materials. The Surface Area is nearly identical for the two materials also. The properties of the slurry were measured after slurry stabilization and are given in Table 1. Properties of a modified slurry are also presented in Table 1. This is explained later in the paper.

Table 1. Slurry Properties of Alumina Slurry

Property	Units	200/325 Slurry	Modified Slurry	Comments
Zahn #5	Seconds	25.1	25.0	
Density	grams/cc	2.55	2.64	
Surface Tension	dynes/cm	32.4	32.6	
Plate Weight	grams	1.56	1.72	Buntrock Small Plate
Coating Thickness	mm	0.076	0.092	On glass slide

During testing of the 200/325 Alumina slurry, it was noted that the draining was poor and the slurry continued to drip for a long time. To investigate the poor draining, we measured the Brookfield viscosity of the slurry. An important characteristic of slurries and how they perform is their viscosity at variable shear rates. Most investment casting slurries are non-Newtonian, which means that their viscosity is independent of shear rate. Water, for example, has the same viscosity independent of how fast it is stirred. Investment casting slurries are not that simple. A Brookfield viscometer is often used to measure the viscosity of non-Newtonian fluids. A Zahn cup can not be used for this type of measurement. A Brookfield Viscometer is shown in Figure 2. The spindle is turned at various selected speeds and the viscosity is displayed and recorded. There are also various sizes of spindles, if needed, for higher or lower viscosity materials. Spindle 3 was used for all the measurements in this paper. The Brookfield viscosity of the 200/325 Alumina slurry was measured and is shown below in Figure 3 along with the Brookfield viscosity curve of the modified slurry, which is explained later.

Figure 2. Brookfield Viscometer

.

Looking at the 200/325 Alumina slurry viscosity curve (Figure 3), reveals that the overall viscosity is low even though the #5 Zhan viscosity is fairly high (25 sec.) . Additionally, the Brookfield viscosity curve increases at the higher RPM values. Neither of these features is desirable. In order to improve the slurry, I added 6% by weight of finer particle size Alumina. This Tabular Alumina had an average particle size of 5 microns and a surface area of 3.36 sq.m/gram. The particle size distribution of the original 200/325 slurry and the Modified slurries are shown in Figure 4. Significant improvements were made in correcting the draining of the slurry, and slurry properties. See Table 1 again to compare the properties of the two slurries.

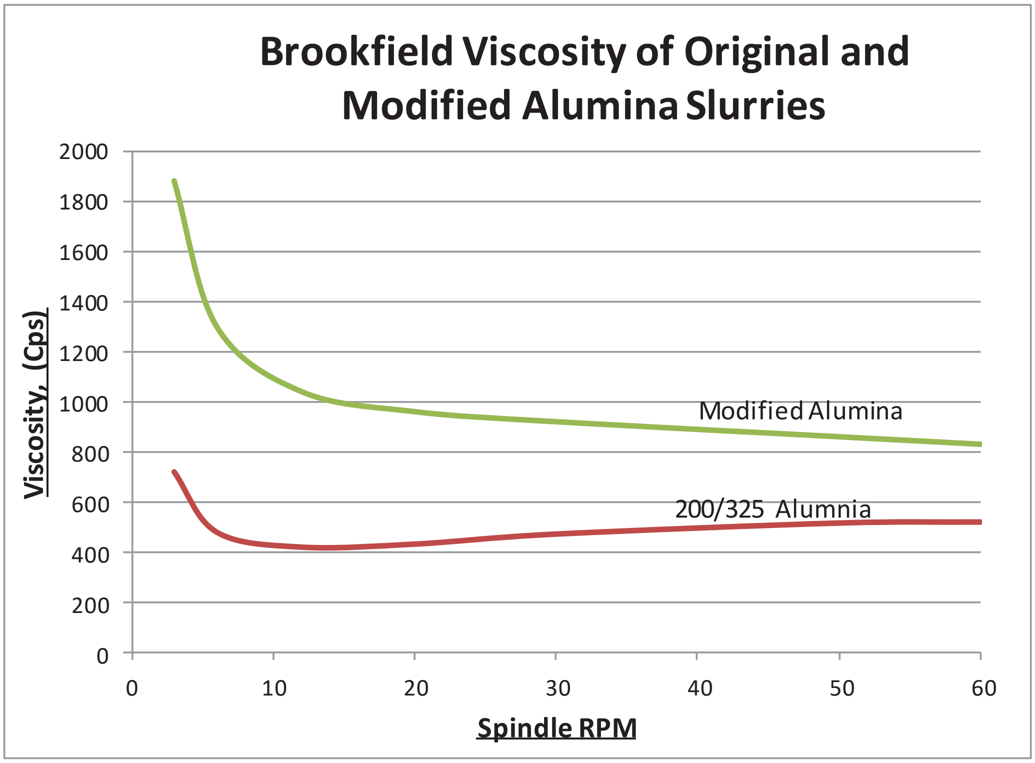

Figure 3. Brookfield viscosity curves for two Alumina slurries.

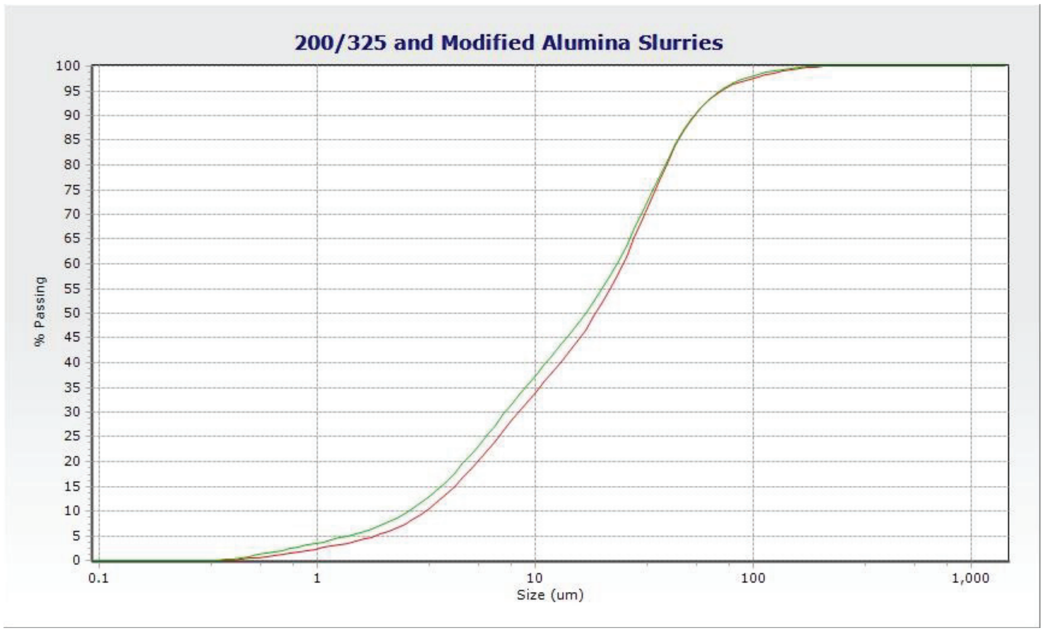

Figure 4. Paricle size of the 200/325 and Modified Slurries. Green is Modified Slurry.

Discussion

Investment casting prime slurries can be greatly affected by particle size distribution of the flour being used. Many critical slurry properties drainability, wet coating thickness and slurry density can be altered by seemingly small changes to particle size distribution. These slurry properties can have an influence on casting quality. It has been shown that just using standard refractory material can result in undesirable slurry properties. Therefore, better particle size control of refractory powders is needed and can be done with additional effort. The data presented here is not intended to be a recommendation for any particular particle size distribution, but is merely to demonstrate how a seemingly small difference in particle size distribution can affect slurries and potentially castings. Buntrock Industries currently does this type of higher level of control of particle size for customers purchasing Yttria and Zirconia powders for Ti casting and Alumina powder for DS/SC applications in three domestic and 4 foreign investment casting companies.

INVESTMENT CASTING INSTITUTE

Autonomous Engineering Applied to Investment Casting Processes

Gerald Richard
MAGMA Foundry Technologies

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 10

Autonomous Engineering applied to Investment Casting Processes

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ABSTRACT

Investment casting foundry engineers have been using casting process simulation tools to optimize casting designs and processes for years with the goal of finding the best compromise between casting quality and cost. Time is the most precious commodity in foundries and it is strictly limited by the (more and more limited) number of skilled employees available, as well as the delivery requirements the foundry's customers demand. The time it takes to evaluate all potential options to finding the optimal casting process configuration by manually simulating them always exceeds the total time available to the engineer. Autonomous optimization the main component of a new methodology called Autonomous Engineering, which is introduced by MAGMA®, the provider of the casting process simulation tool MAGMASOFT®, relieves the foundry engineer of the majority of this “manual labor”. The software offers two autonomous optimization options, complementing, and potentially replacing, the traditional manual simulation option. This presentation will show examples of investment castings where Autonomous Engineering was utilized to eliminate casting trials and resolve casting defect issues.

INTRODUCTION

Lowering manufacturing costs and reducing delivery times are generally a primary concerns for investment casters, casting designers, casting buyers, and virtually anyone involved with producing a casting. When designing gating systems the primary concern is often on quality with manufacturing costs as a secondary concern due to looming PPAP submission deadlines. If during this design phase hundreds or even thousands of different gating systems can quickly be evaluated, then both quality and manufacturing costs can be considered and even weighed against one another. Since pouring hundreds of sample castings with different gating systems is not practical, using casting process simulation with integrated autonomous optimization capabilities is a much more practical solution. One challenge to the accurate simulation specific to the investment casting process is the sensitivity of the process to the thermophysical properties of the ceramic shell. Each investment caster uses, sometimes multiple different, proprietary compositions making shells customized for their process requirements. This usually requires simulation users to manually fine-tune thermophysical property datasets. With autonomous optimization, there is now a tool available to automate that process through running an inverse optimization. The first example in this paper will demonstrate that process in a commercial application. Two more examples show how simulation was used in art foundries to prevent defective castings.

EXAMPLE 1 – DATA ACQUISITION

American Foundry Group (AFG) produces as much as 2000 tons of steel castings each year, primarily serving the pump and valve industry. These steel castings range in size from less than 1 lb to 6500 lbs with both sand and investment capabilities.

AFG uses MAGMASOFT® to analyze the solidification and filling of castings. They have been able to reduce the amount of time to sample new jobs and have reduced the number of problem jobs. Still, it appeared that the software was too conservative in predicting porosity defects. In an effort to increase the accuracy of predicting shrinkage porosity, AFG decided to fine-tune the thermal properties of the shell material datasets. Because of a variety of shell compositions, particle size distributions and processing parameters it is unlikely that one general thermophysical property dataset can be used to describe every foundry's ceramic shell. The first step to validating a shell's thermal property is to accurately collect continuous temperature data from the mold. In this study AFG chose to measure the center of the mold cavity and the outside of the mold. Figure 1 shows the test block used and where the thermocouples are placed.

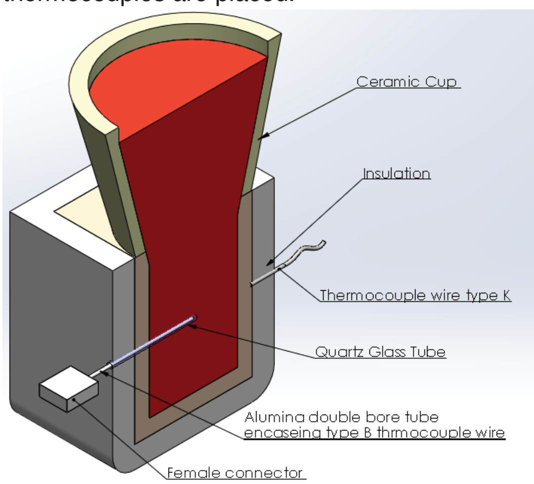


Fig. 1. *Test block with thermocouple placement in mold*

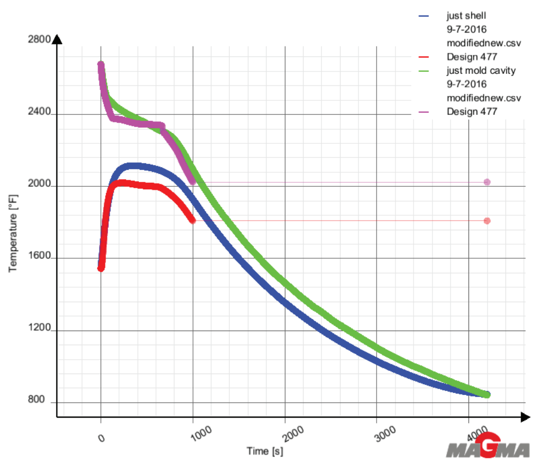
In order to accurately and securely place the thermocouple in the mold, a glass tube for containing the thermocouple in the center of the casting was molded into the wax test block as shown in figure 2.

Fig. 2. *Glass tube placement.*

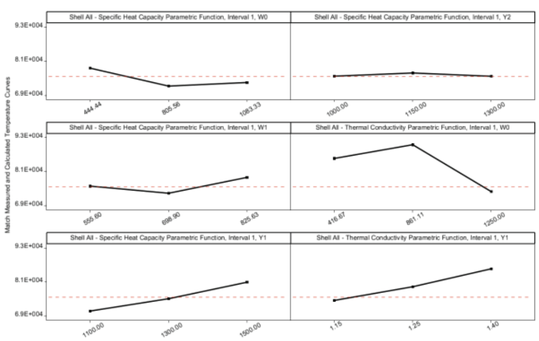
After de-wax the outside of the glass tube was exposed so that the probe could be inserted. For the thermocouple on the outside of the shell a thermocouple was placed at a depth of eighty thousandths of an inch into the shell. To maintain a consistent shell composition the same binder and sand was used to backfill the hole as was used for the final dip. Insulation was wrapped around the mold to minimize the impact of the air temperature. The shell was placed in the oven to cure and be preheated for pouring. By running the thermocouple wire out of the oven, data collection could begin before the shell is out of the oven, which allows for seeing the temperature drop from the oven to the pouring tray. Once the mold is on the pouring tray, the thermocouple probe is inserted into the glass tube and temperature readings are from inside the casting recorded.

EXAMPLE 1 – INVERSE OPTIMIZATION

Inverse Optimization is a methodology used to match measured and simulated data. Virtual thermocouples are placed in the same locations in the simulated mold, as in the real mold. Using measured temperature data from the foundry and output temperature data from simulations, the software changes variables with the intent of reducing the area between the curves and eliminating the difference in slopes between them as well. If the measured and simulated cooling curves match, the simulation accurately predicts the heat flow passing through the shell, which will have an impact on all simulation results. Two variables of the shell data were evaluated: 1) the temperature dependent specific heat capacity and 2) the temperature dependent thermal conductivity. The software varied both in an effort to match the simulated with the measured cooling curves in the center of the casting and on the surface of the shell. Theoretically, there would have been 553,350 possible combinations to be evaluated. However, as the software approaches this so-called design space in a very efficient manner by essentially learning “on the go” about what changes in the variables have the most impact on making the curves match, only 640 simulations were actually run. The best one is shown in graph 1. The curves for the casting match very well, while the ones for the shell can be improved. Through reviewing of the main effect charts (Graph 2) it was determined to focus on modifying a certain temperature



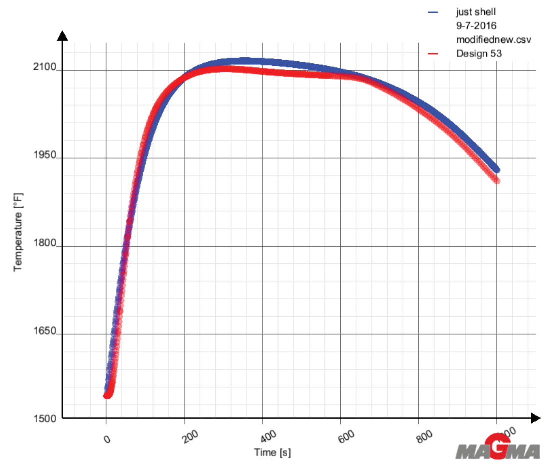
Graph 1. *Measure vs. Simulated Temperatures*



Graph 2. *Main Effect Charts*

segment of the thermal conductivity curve, as this showed the biggest impact on moving the simulated temperature curve closer to the measured one. This time only 80 of the 341 possible designs needed to be run.

The best match between the measured and simulated shell temperature is shown in graph 3, while figure 3 shows what impact the changes made in the thermophysical property dataset of the shell material actually have on the prediction of porosity results. The results now show that the alloy feeds better than previously simulated. This behavior matches the real world experience of AFG much better than the original setup.



Graph 3. *Best mold temperature match*

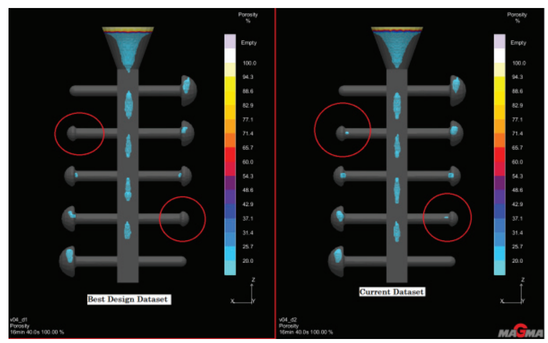


Fig. 3. *Impact of dataset change on porosity prediction*

EXAMPLE 2 – PROCESS WINDOW EVALUATION

Form3d Foundry in Portland/OR wanted to evaluate the proposed gating system and process parameter configuration for the casting of a sculpture regarding its ability to fill the casting without misruns or cold shots and avoid surface or internal defects. The initial filling and solidification simulation showed satisfactory results for the filling behavior and temperature distribution during and after the filling process (Figures 4, 5 and 6).

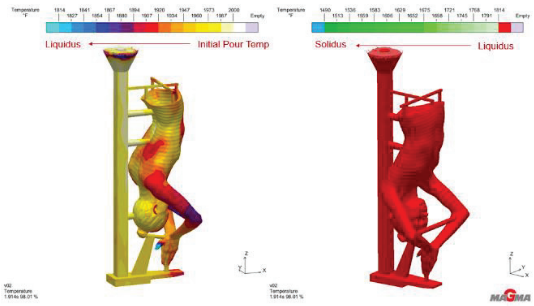


Fig. 4. *Melt temperatures stay above Liquidus until melt rests in its final location*

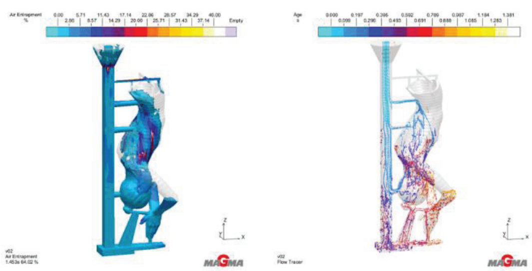


Fig. 5. *Filling process results show only a minor potential for air entrapment and inclusion potentially leading to surface defects*

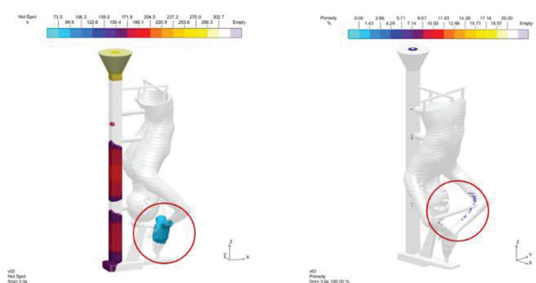
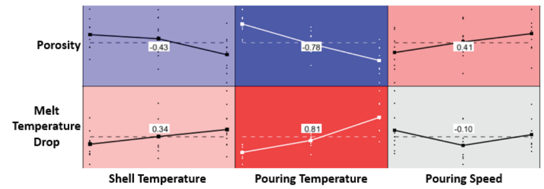


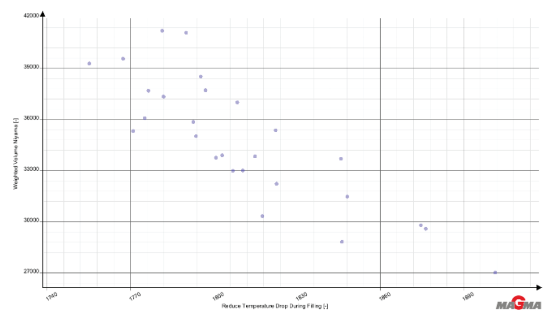
Fig. 6. *Only a minor potential for surface shrinkage defects were detected*

The question was posed if this single simulation of one process point is representative of the production process, which experiences potential variations in process parameters. Predominant ones are the shell temperature, the pouring temperature and the pouring speed. Traditionally a simulation engineer now would have to set up several separate simulations with each process parameter combination. Fortunately the simulation tool used simplifies that process, as it allows the engineer to set up all desired process parameter variations in one setup. The program then runs all parameter combinations of this Design of Experiment (DoE) and at the end provides statistical information to the engineer. In this case the main effect diagrams showed that the shell temperature and the pouring speed has a smaller impact on the temperature loss during the filling process than the pouring temperature (Graph 4).



Graph 4. *Impact of shell and pouring temperature, as well as pouring speed on temperature drop and porosity defects*

However, they also show that the pouring speed produces more shrinkage defects. Interestingly a higher final temperature at the end of the filling process also creates less porosity, which is confirmed by the scatter chart where each dot represents one simulation run (Graph 5).



Graph 5. *Impact of higher pouring temperature on porosity defects*

Overall, the DoE showed that a slower pouring speed at a higher temperature is beneficial no matter at what shell temperature. It also showed that no parameter combination in the process window produces non-acceptable castings, so the gating system is robust for the given process window.

EXAMPLE 3 – RISER OPTIMIZATION

West Supply in Chicago/IL was collaborating with MAGMA on designing a gating system for an art casting. The gating system should lead to good castings in combination with the lowest cost. Some of the biggest cost factors are the amount of material used and the labor involved to remove gates and risers. The basic geometry is shown in figure 7.

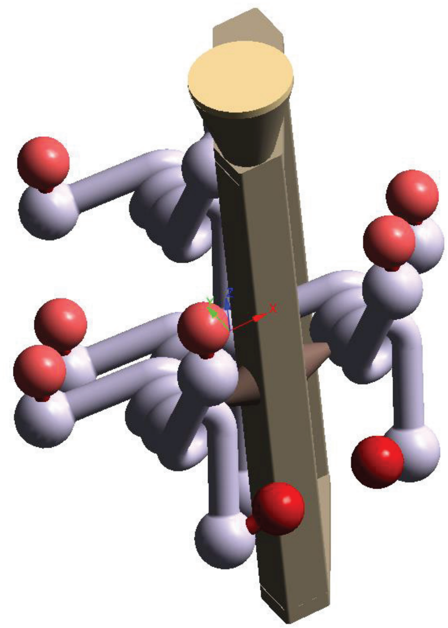


Fig. 7. *Geometry setup with castings (grey), risers (red) and tree (brown)*

The engineers working on this casting quickly agreed on the basic setup requiring risers and gates. However, finding the optimal combination of riser size, riser contact size the casting and gate contact size to the tree usually requires tedious and repetitive simulation setups with small variations in each of these geometry features. In addition, a process parameter like the varying shell temperature could have an impact on the quality of the casting. Sophisticated radiation models are required in simulation tools to accurately predict the shell surface and internal temperatures at every step of the investment casting process (Figure 8).

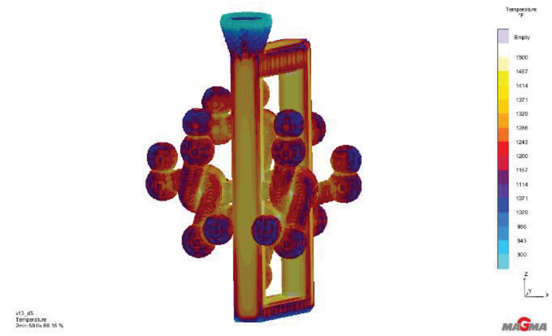
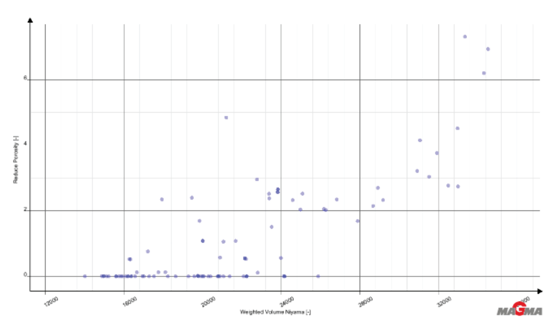


Fig. 8. *Shell temperature distribution*

Varying all these geometry features and the shell temperature and trying to simulate all potential combinations (called designs) would require an unpractical time for the simulations to run or computer resources usually not accessible to investment casting foundries. The simulation tool used eliminates the need to run all designs by taking a systematic approach of selecting a group of initial designs providing a good representation of the entire design space. Running this group of initial designs, it evaluates which ones show promise to lead to defect free, low cost castings. It finds the parameters that have the biggest beneficial impact on the desired outcome. The software then selects another set of designs based on what it learned from the first group of designs simulated. Thereby it hones in very quickly on the optimal geometry feature and process parameter combination, eliminating the need to run all potential designs. Graph 6 shows the scatter chart of all designs that were run.



Graph 6. *Comparison of all designs regarding porosity and cost. Best designs are on the lower left of this chart*

Graph 6 shows all simulations that were run autonomously (without interaction of the engineers) by the software. The best ones with the lowest porosity at the lowest cost to produce are found near the lower left hand corner of the chart, the worst ones on the upper right hand corner. Figure 9 compares the shrinkage defect prediction of the best and the worst design.

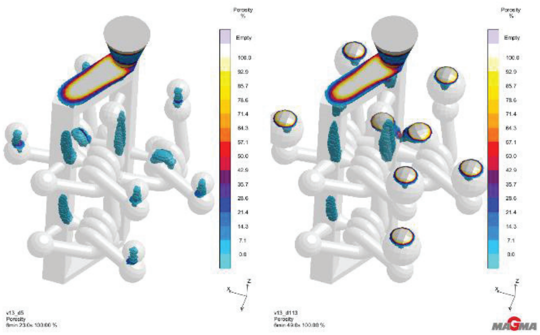
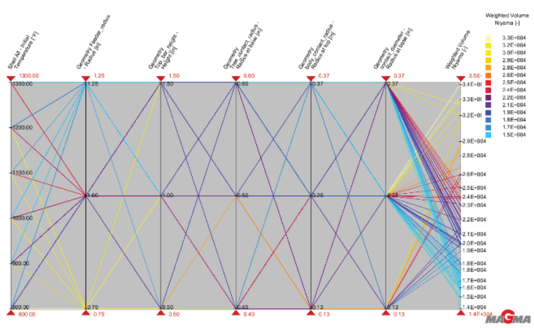


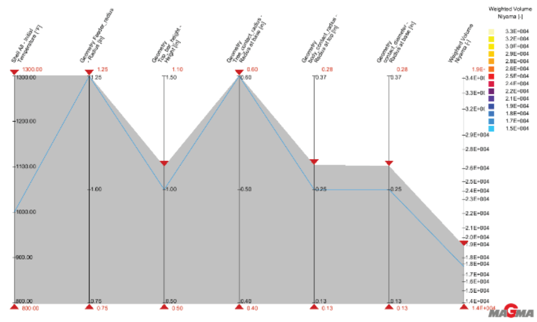
Fig. 9. *Worst (left) and best (right) design, the latter leading to a defect free casting*

Understanding of which parameter combination leads to the best casting is essential to a successful development of a casting process for a particular investment casting. In Graph 7 each line represents a specific combination of geometry features and shell temperature.



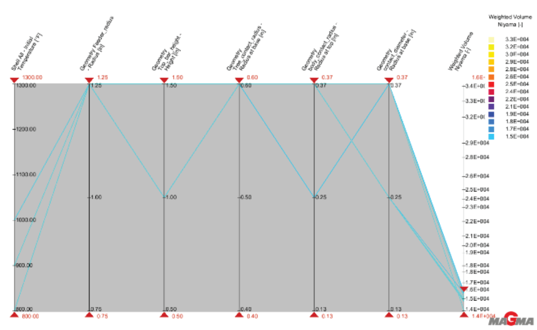
Graph 7. *Plot where each line represents one set of parameter combinations simulated*

Moving the red slider down on the right hand side leaves only the ones with acceptable shrinkage defect levels (Graph 8).



Graph 8. *Parameter combinations with acceptable shrinkage defects*

As all other parameters are the more costly the larger they are (riser diameter, contact areas, etc.), it is imperative to find a design that minimizes these values, thereby minimizing costs, in combination with acceptable casting quality. These interactive charts, provided within the simulation tool used for this work, allow engineers to choose the best compromise between lowest cost and casting quality. They can make the decision to simply choose the one with the lowest porosity. However, that might not be the most cost effective configuration. For instance the casting made in the configuration shown in Graph 9 would be slightly “cleaner” but significantly more expensive to make.



Graph 9. *Parameter combinations with acceptable shrinkage defects*

CONCLUSION

Using the capability to autonomously run virtual designs of experiments optimizations to find optimal casting process parameter and design feature combinations to make quality castings at minimal costs is the core benefit of autonomous engineering methodology integrated into the casting process simulation software

MAGMASOFT®. Three investment casting examples were used to show how the accuracy of simulation tools can be increased by using customized thermophysical property datasets for investment casting shells in combination with sophisticated radiation models. Additionally it was show how autonomous design of experiments and optimizations can prove process robustness and find the best compromise between casting quality and cost.

INVESTMENT CASTING INSTITUTE

Update on ICI–AFS Joint Research Project on the MMPDS Inclusion of 17-4 PH & 15-5 PH Investment Cast Steels

Al Torok – Yamaha Marine Precison Propellers, Inc.
Jiten Shah – Product Development & Analysis (PDA) LLC
Zayna Connor – Consultant

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

ICI / AFS Report

Update on ICI-AFS Joint Research Project on the MMPDS Inclusion of 17- 4 PH and 15 – 5 PH Investment Cast Steels

by
Al Torok, Yamaha Marine Precision Propellers, Inc.
Jiten Shah, Product Develpment & Analysis (PDA) LLC.
Zayna Connor, Consultant

Abstract

Authors will give an update on this project which was presented at the last congress. Testing is undergoing for various tests as required by MMPDS using over 500 test plate castings and 600 cast integral test bars for a total of 3 different heat treatment types for each alloy per AMS specifications. Test plates were provided by 14 investment foundries, majority serving aerospace industry. The funding for the project was provided by DLA to AFS with in-kind cost share support from various participants.

Update on ICI-AFS Joint Research Project on MMPDS Inclusion of 17-4 PH and 15-5 PH Investment Cast Steels

Dr. Zayna Connor

VP-Technical Services, American Foundry Society

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Investment Casting Technical Manager

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ICI Annual Meeting – October 2017

Current Cast 15-5PH and 17-4PH Data in MMPDS-07

The cast 15-5PH and 17-4PH Data (Section 2.6.7-2.6.9)

- **2.6.7 15-5PH**
  - **Table 2.6.7.0(a). Material Specifications for 15-5PH Stainless Steel**
    - AMS 5400 Investment casting (H935)*
- **2.6.9 17-4PH**
  - **Table 2.6.9.0(a). Material Specifications for 17-4PH Stainless Steel**
    - AMS 5342 Investment casting (H1100)*
    - AMS 5343 Investment casting (H1000)*
    - AMS 5344 Investment casting (H900)*
      - ***Only have S-basis data.**

Highlighted in red blocks are the grades being tested for the inclusion.

AMS Casting Material Specifications fpr 17-4PH & 15-5PH					
	180ksi (H900) (1)	180ksi (H925) (2)	170ksi (H935) (2)	150ksi (H1000) (2)	130ksi (H1100) (2)
17-4PH	AMS 5344 (3)			AMS 5343 (3)	AMS 5342 (3)
15-5PH		AMS 5346	AMS 5400 (3)	AMS 5347	AMS 5356
	(1) Precipitation hardened at 900-925F				
	(2) Precipitation hardened at the designated H-Temperature				
	(3) S-Basis in MMPDS-07				

Test Plan - Properties being evaluated

1. Conduct MMPDS required tensile, compression, modulus and shear; Charpy and tensile (from both cast integral as-cast test bar – S basis as well as extracted off the test plate) for both the alloys and all three heat treat types for each - total 6 sets
2. MMPDS pin bearing and fatigue from as-cast specimens for both alloys and only one heat treat type, which is currently populated in the current MMPDS/MIL handbook – **17-4PH with H1000 and 15-5PH with H935.**

17-4/15-5 PH Project
List of Participating Foundries (14)

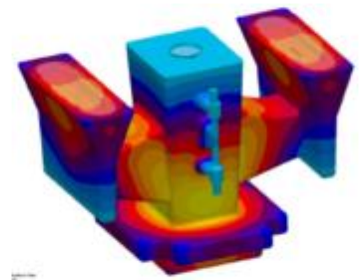
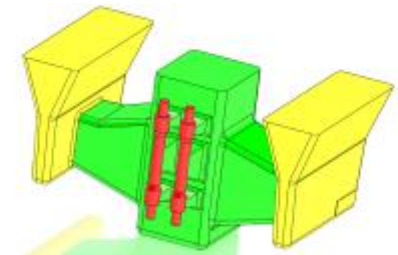
- Precision Propeller Industries / Yamaha-Motor
- Signicast, WI
- Carley Fdy, MN
- MCM Precision Castings Inc, OH
- MetalTek International, Wisconsin Investcast Div
- Tech Cast, Meyerstown, PA
- Kovatch Castings
- Aerotec Alloys
- DAFCO Aerospace (Damaeron)
- Intercast - Fansteel
- Wisconsin Precision Casting
- Eagle Precesion Casting Co, NJ
- Aristocast, MI
- Bescast, Inc

Total 1600 tests from over 500 test plates and 600 cast test bars !

Project Completion Plans 17-4/15-5PH

Statistical Properties for MMPDS Standard (CHAMPS) (AFS)
Statistical Properties of 17-4/15-5PH for MMPDS
✓ Complete modeling of rigging
✓ Complete tooling and make test waxes
✓ Complete making waxes, assembly trees and ship to foundries
✓ Complete casting of MMPDS test plates & separately attached bars
✓ Receive plates at AFS and spend for X-ray
✓ Send plates for heat treat
Complete MMPDS Mechanical Testing & Compile Results
Submit 17-4/15-5PH to MMPDS

Special Thanks & Acknowledgement

1. **Project Sponsors**:
   - DLA-POC : Dean Hutchins
   - AMC-AFS
   - ICI
2. **Project Management Team**: Dr. Zayna Connor(AFS) - PI, Jiten Shah-Project Manager (PDA -Product Development & Analysis), Al Torok- Precision Propeller Industries, Inc. (AFS 4L and ICI Technical Committee Liason)
3. **Suppliers** (Wolf Aerospace) (MPI) (Paramelt), MIL (NDT), Applied Thermal Technologies (Heat Treater) and Metalcasters with in-kind support and efforts

Thank You !!

For more information:

contact Dr. Zayna Connor at zconnor@afsinc.org

or

stop by at ICI Booth #434

or

contact **Jiten Shah** at i**nfo@PDA-LLC.com**

INVESTMENT CASTING INSTITUTE

Case Study: Recruitment & Retention Challenges of Today & Beyond

Tim Sullivan
Hitchiner Manufacturing

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Panel Discussion

Recruitment and Retention Challenges of Today and Beyond

by
Timothy C. Sullivan, Esq.,
Hitchiner Manufacturing Co., Inc.

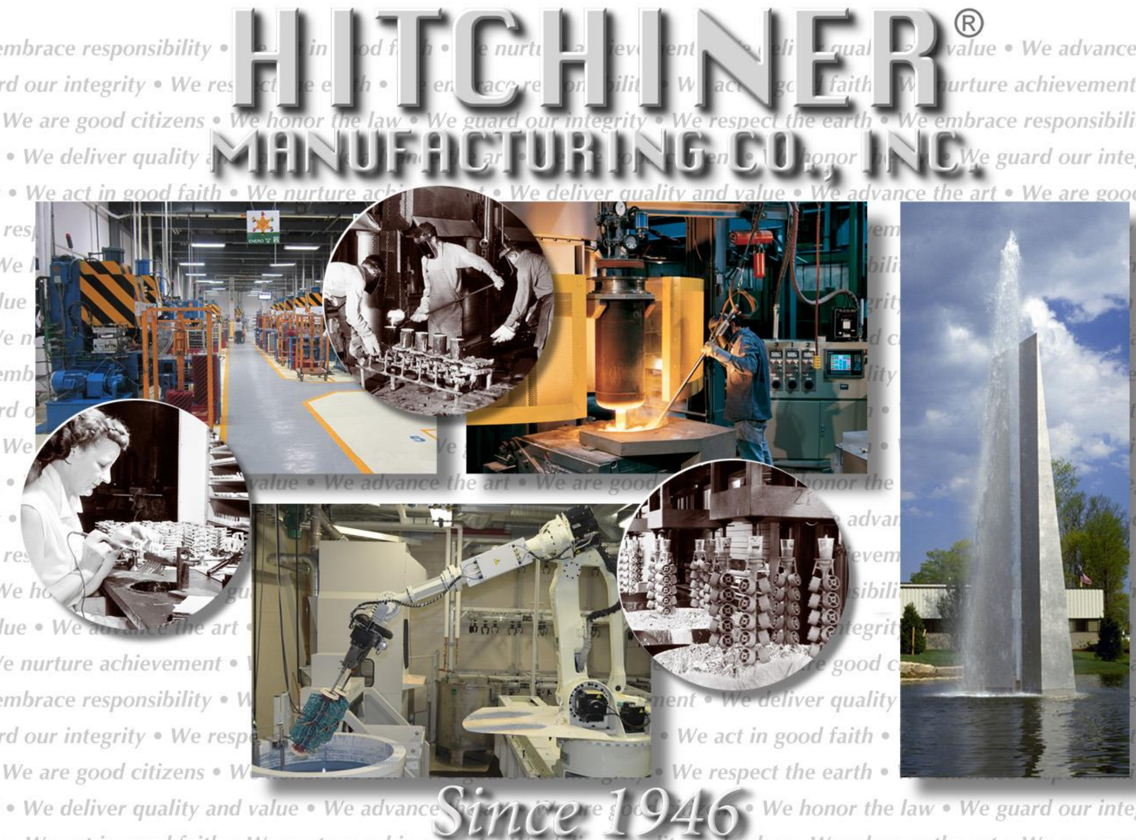
Abstract

In 2015 and as a means to improve product flow, reduce lead time, reduce WIP inventory and reduce fixed overhead, Hitchiner made a decision to close its Littleton, NH facility and consolidate those post-cast finishing operations to its corporate headquarters in Milford, NH, located approximately 125 miles away. The closure affected approximately 135 employees, all of whom were guaranteed jobs in Milford, along with relocation benefits. When less than 10% of the Littleton workforce agreed to relocate, it created a critical shortage of skilled and semi-skilled finishing, NDT and machine tool operator labor. The situation was compounded due to high turnover amongst millennials and an unemployment rate that was plummeting to 2.5%.

The presentation will describe:

1. Existing work environment positives, wage and benefits philosophies that helped attract a new workforce;
2. New initiatives deployed to increase applicant pool, as well as what worked well, and what didn't, and
3. Ongoing measures to attract and retain exempt and nonexempt workforce in anticipation of future labor shortage in the State.

Recruitment & Retention Challenges Today and Beyond



Timothy C. Sullivan, Esq.
Vice President, Corporate Affairs and Services, Inc.

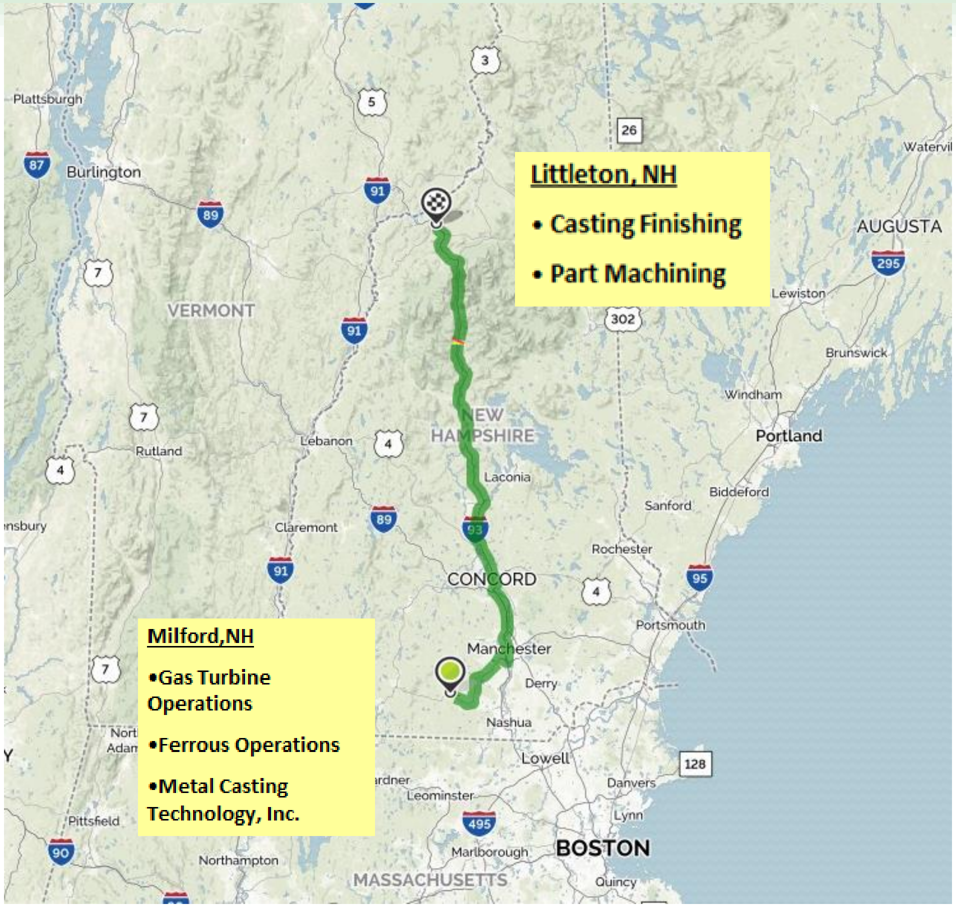
Recruitment, until recent years…

- Would be applicants arriving every day, looking for work
- 8 out of every 10 – a potential hire
- Never advertised job openings, except roadway signage

Pay and Benefits Philosophies

- Annually benchmark wages
- Set pay scales to 75^{th} percentile
- Established career pathways
- Competitive benefits

Littleton Wind Down



https://www.youtube.com/watch?v=BEts4MtN2AI

The Perfect Storm

- Hire 120 skilled/semi skilled persons
- Maintain workforce at other Milford operations
- Low unemployment
- Poor quality applicant pool
  - 2015: hired 350 hourly to retain 125

NH Unemployment

N H PPS New Hampshire Center for Public Policy Studies

Going forward, the rate at which employers add workers is expected to slow and eventually come to a halt, not so much due to weaker demand on their end, but rather because the inventory of workers from which the public and private sector can select from to expand their operations will be extremely limited.

Part of this tight inventory stems from the extraordinarily low level of unemployed residents. It is also being driven by a momentous shift in the state's demographic landscape.

For example, the number of residents between the ages of 20 to 64 years old, a rough definition of the working-age population, is anticipated to modestly decline over the coming years, as the much-publicized graying of the baby boom generation continues to unfold. Economic growth, whether measured by payroll employment or gross state product, will slowly decelerate over the course of 2017 and 2018, before coming to a standstill, as employers confront a scarcity of available labor.

NH Unemployment Forecast

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Unemployment Rate (%)	5.5	5.1	4.3	3.4	2.8	2.5	2.5	2.5	2.5
Change	0.1	-0.4	-0.8	-0.9	-0.6	-0.3	0.0	0.0	0.0

Lean Implementation

	Pre Kaizen Process	Model Cell	% Change
# of Employees	18	6	66%
Sales $/Emp/Hour	$392	$1,175	199%
Pieces per Hour	4*	9 - 12	175%

***Pre Kaizen pieces per hour did not include Final Inspection**

Workforce Development
High Schools

- Career & Workforce Development Committee
- Participant on Manufacturing & Machine Technical Advisory Boards
- Host engineering job shadow with pre-engineering students
- Internship Program
  - Hitchiner has a long history of supporting the high school internship program (engineering, IT, sales & marketing, etc.)
- Support media promotion of Milford's Career & Technical Education (CTE) programs focusing on the internship program
- Participate in STEM Night to encourage middle school girls to participate in manufacturing and pre-engineering courses at the high school
- Sponsor scholarships to a manufacturing camp at Manchester Community College

Workforce Development Community Colleges

- NDT Advisory Committee.
- Advisory board for Advanced Manufacturing and Robotics Program.
- Member of the Advanced Manufacturing by Innovation and Design (AMID) Advisory Committee which advised NCC on TACCT grant spending which allowed for the expansion of their advanced manufacturing programs.
- Tuition assistance and time off from work for employees to obtain Robotics Certificate.
  - Completion of three courses in this certificate allows employees to advance to Automation and Controls Technician role. (After moving into the role, employee has two years to complete the certificate.)

Workforce Development Community Colleges

- Through our educational assistance program we support current employees in advanced manufacturing.
- Participating in NH Manufacturing Week Open House.
- Supervisor, Layout and Supervisor, Tooling both have provided input and support in the development of NCC's new advanced manufacturing programs.
- Supervisor, Layout teaches metrology which is part of the newly created Metrology Certificate and, at another college, Solidworks.

Workforce Development
4 Year Colleges/Universities

Keene State College

- Hitchiner Engineering Certificate
- Keene State Manufacturing Partners Scholarship
- Career Speakers Series

University of New Hampshire

- Four students currently working towards MBAs through Hitchiner's educational assistance program. Three of whom have bachelor's degrees in engineering.
- Engineering job shadow
- Hire summer engineering interns upon graduation

Workforce Development Other

- NH Manufacturing Week
- Summer Internship Program
- Donated Equipment
- New Hampshire Manufacturing Sector Partnership
- Skillist Pilot Project
- MYTURN
- Lean training and implementation

https://www.youtube.com/watch?v=Tbjdx4Qd3hY

FRIDAY OCTOBER 7, 2016

Creating a Buzz with the New Hampshire Manufacturing Partnership

PATRICIA MAGUIRE

By Patricia Maguire and Deborah Kobes

This summer, Governor Maggie Hassan, Commissioner Jeffrey Rose, over 20 New Hampshire manufacturers, and over 30 workforce and education programs gathered at Hitchiner Manufacturing to discuss the current state of the manufacturing sector, pressing current and future workforce needs, and how a statewide sector partnership can be a solution.

NH BUSINESS REVIEW

HOME NEWS PEOPLE BUSINESS ADVICE OPINION REAL ESTATE EVENTS &

New Hampshire Business Review / May-27 2016 / Health Innovator Award: Hitchiner Manufacturing

Health Innovator Award: Hitchiner Manufacturing

BY JULIA K. AGRESTO

0

Published: May 27, 2016

Roseda Rith, RN, left, takes Hitchiner Manufacturing Chairman & CEO John H. Morison's blood pressure at the company's onsite health and resource center in Milford. Looking on at center is medical assistant Lois Viveney. Both Lois and Roseda are Foundation Medical Partners employees.

For leading the way when it comes to offering outstanding health and wellness programs for employees, Hitchiner Manufacturing has been recognized by Harvard Pilgrim Health Care and NH Business Review as the most recent Health Innovator Award recipient.

Founded in 1946 and headquartered in Milford, Hitchiner Manufacturing Co., Inc. is the premier supplier of complete-to-print, high-volume, complex thin-wall investment castings and fully-finished casting-based subassemblies and components to industry.

Q. What makes Hitchiner Manufacturing an outstanding company to work for when it comes to health and wellness?

NH BUSINESS REVIEW

HOME | NEWS | PEOPLE | BUSINESS ADVICE | OPINION | REAL ESTATE | EVENTS &

New Hampshire Business Review / June-23 2017 / Hitchiner Manufacturing hires MY TURN graduates

Hitchiner Manufacturing hires MY TURN graduates

Training program for unemployed and underemployed high school graduates produces results

BY LIISA RAJALA

0

Published: June 8, 2017

Nine of the program's graduates present their certificates with some representatives representatives from Hitchiner Manufacturing, MY TURN and Nashua Community College.

Nine students have completed the joint training program created by Hitchiner Manufacturing Co., the Manchester nonprofit MY TURN and Nashua Community College. All nine have been offered entry-level positions with the Milford manufacturer working in the metal cell, metal grinding and in the machine shop. Seven have accepted positions with Hitchiner while one student has accepted a position with the United States Postal Service and another at a boy scouts summer camp, with plans to return to Hitchiner in the fall.

NH Unemployment Rate

http://www.wmur.com/article/nhs-low-unemployment-rate-poses-challenges-for-employers/9874746

INVESTMENT CASTING INSTITUTE

Case Study: The Merging of Cultures in an Acquisition - Personnel, Systems & Technology

Cliff Fischer
Wisconsin Precision Casting

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Panel Discussion

The Merging of Cultures in an Acquisition: Personnel, Systems and Technology

Cliff Fischer
Wisconsin Precision Casting Corporation

Abstract

Since before the acquisition of Northern Precision Casting Co. Inc., Lake Geneva, WI was publically announced in January 2015, Wisconsin Precision Casting Corporation (WPPC) was fully aware that the merging of these two operations would result in its own set of challenges, unlike those previously faced by either facility. From things as simple as telephone system compatibility to the weighty challenges of merging technical practice and social cultures into a single cohesive company, WPPC leadership had to concern itself in all aspects of this undertaking to ensure success.

This case study addresses some of issues and challenges that WPPC and its two divisions were faced with, their adaptation to a new social, technical and environmental culture, and lessons learned along the way.

Wisconsin Precision Casting Corporation

Divisions in Lake Geneva & East Troy - WI

- Cliff Fischer – VP Operations / Co-Owner

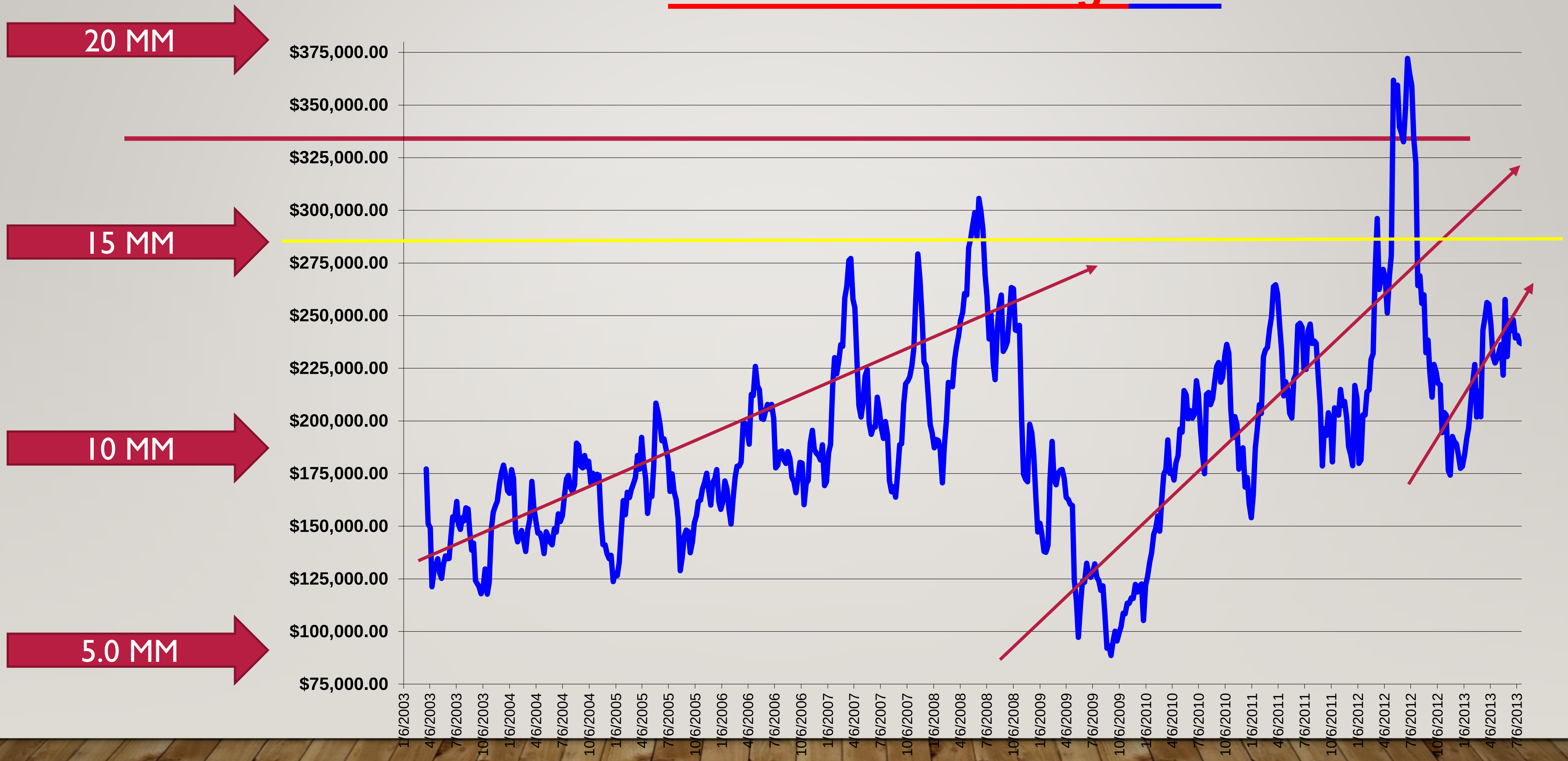
our acquisition story

Culture Change or Cluture ***Shock***!

East Troy Division

- 38,000 SF
- 65 ee's
- 3 balanced shifts
- 85 molds/day
- 12MM to 15MM

WPCC 12 Week Avg. O.E.



CAPACITY CONCERNS . . . .

- Options
  - Build (New) ………on hold
  - Addition . ……….. pursuing
  - Buy (Existing IC Fndry) ……. not likely yet
  - Merge ………. Not likely yet
  - Prune ☹ ………not on purpose!
  - 24 x 7 ☹ (from 17 shifts/wk. to 21 = +28%) …..No
  - Sub Contract Work to other foundries ….. Pursuing

- *Current Outsourcing Plan*
- *Point Person*

COST / EFFORT OF CONSTRUCTION

- Need approx. 100,000-sf of expansion space
  - Anywhere from $60/sf to $100/sf = $$$$$$ (6MM-10MM)
    - Just a building (No Equipment, No Customers, No Employees, No Sales)
  - Septic Issue . . . (Nearest Sewer over 1-mile away, $$$)
  - Effort to manage the project
  - Customer satisfaction during ramp up

THE PATH BEGAN TO SHOW ITSELF

UTILIZED 5 OTHER FOUNDRIES

- **We were suddenly a customer to other foundries!**
  - **Delivery ☹**
  - **Communication ☹**
  - **Quality ☹**
  - **Pricing ☺**
  - **Lead-Time ☹**
  - **Re-Make Orders ☹**
  - **PPAP / Fixed Process Issues**
  - **Customer Concerns**
- **We rapidly became #2 / #1 Customer to one foundry (clout ?!?)**

THE PATH BECAME CLEARER

MERGE??? / ACQUIRE???

vs Build

ACQUIRE!

Lake Geneva Division

- 102,000 SF
- 76 ee's
- 1.2 shifts
- 300+ molds/day
- 40MM to 50MM
  - (ability)

USING LOGIC AND EXPERIENCE (AND NO BROKER!) FOR DUE DILIGENCE

Appraisal

Contract

Customers

Banking

Attorneys!

Employees

Equipment

Projections

Environmental

ASSET PURCHASE - - - - AND IN THE END

Wisconsin Precision Casting Corporation

Lake Geneva Division

Corporate Headquarters

East Troy Division

Next. . . . . .

Changing a Culture ☺

Simple – we've done it before . . . . .

What is our Culture?

1). SAFETY (Shared Responsibility)
2). Open Door Policy (Don't be afraid to ask)
3). Doing the job right the first time!
4). Personal Responsibility
5). Work Hard / Enjoy What You're Doing
6). Manage by Data & Facts
7). Compartmentalization
8). Fix Things Once and For All (No Duct Tape / Bailing Wire / Oil Dry)
9). Continuous Improvement (Baseball Style!)
10). Walk the Talk of Satisfying Our Customers

Safety

<u>* Note ***</u>**

<u>ALL ACCIDENTS / INJURIES MUST BE REPORTED TO A SUPERVISOR IMMEDIATELY!!!</u>

NO EXCEPTIONS! (per Handbook!!!)

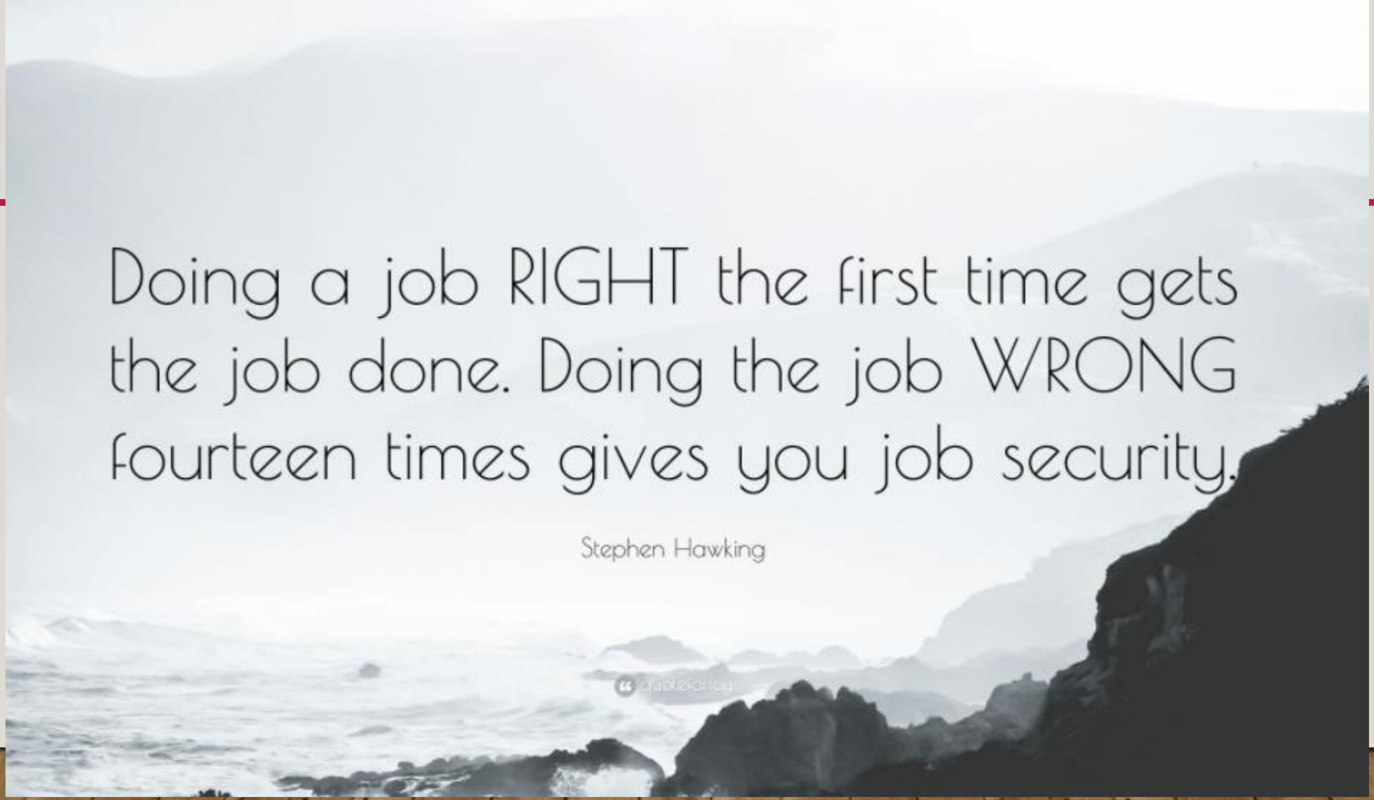
Injuries lead to Accidents!

Always be thinking ahead, be aware of your surroundings –

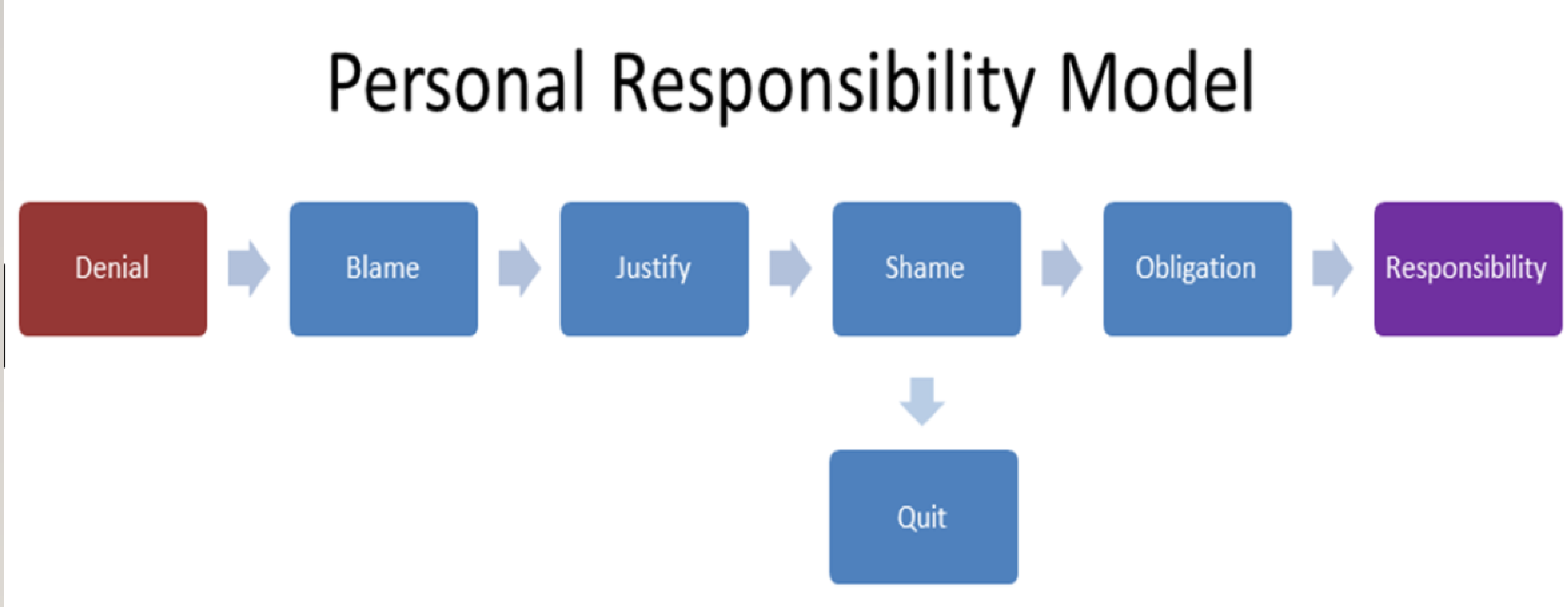
<u>ALL accidents are preventable!</u>

Open Door Policy

Doing the Job Right the First Time

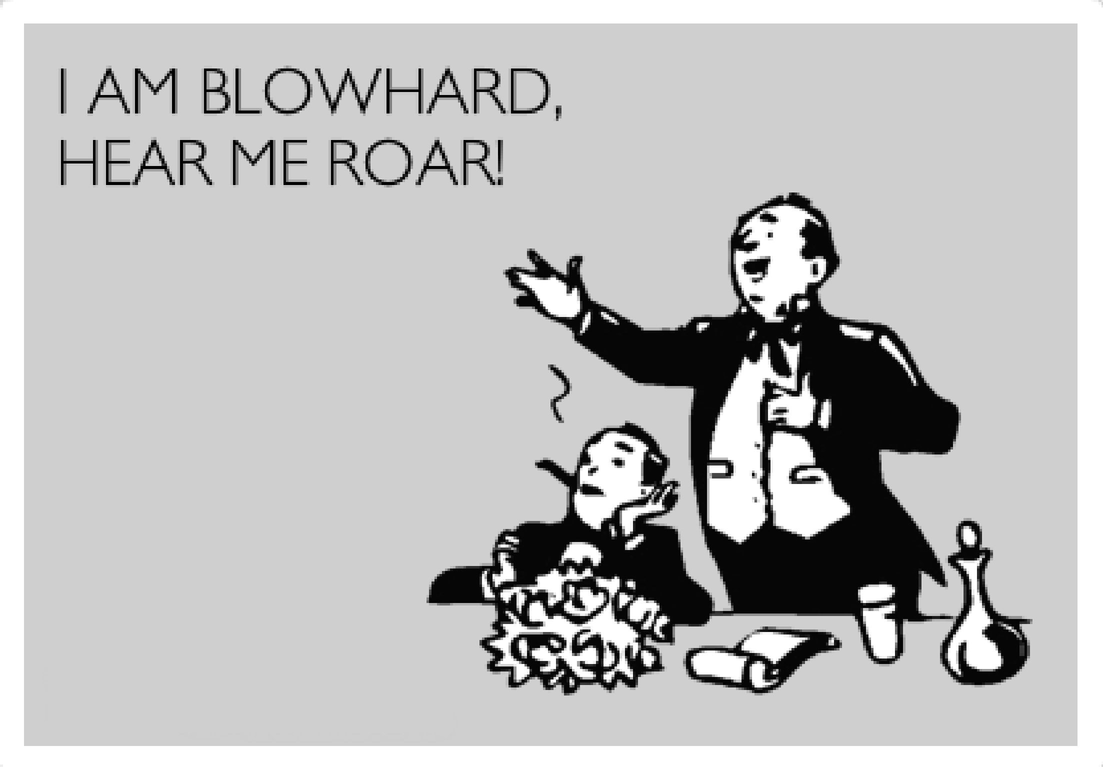


Personal Responsibility



Work Hard
Enjoy What You’re Doing

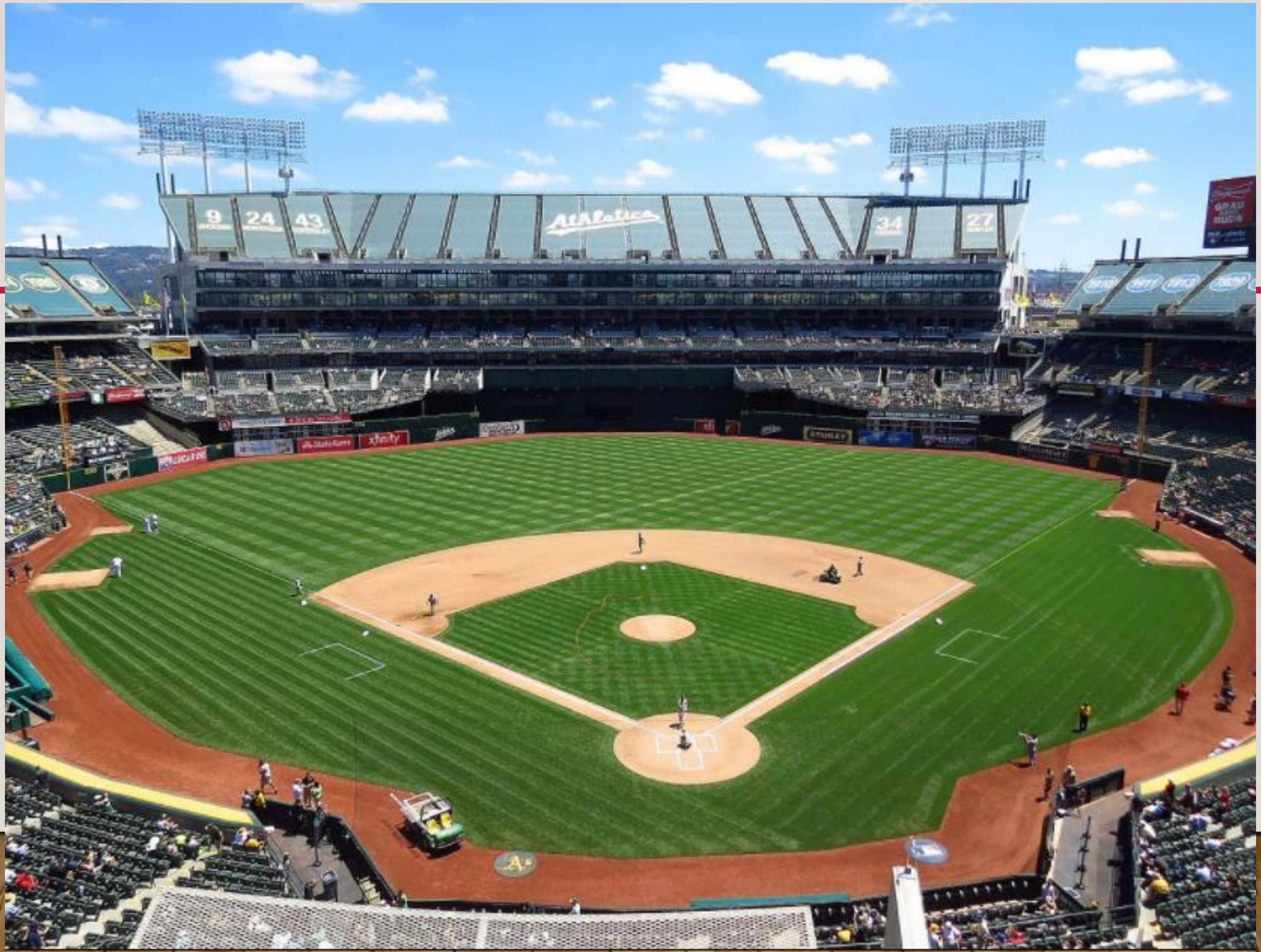
Manage by Data & Facts



Compartmentalization

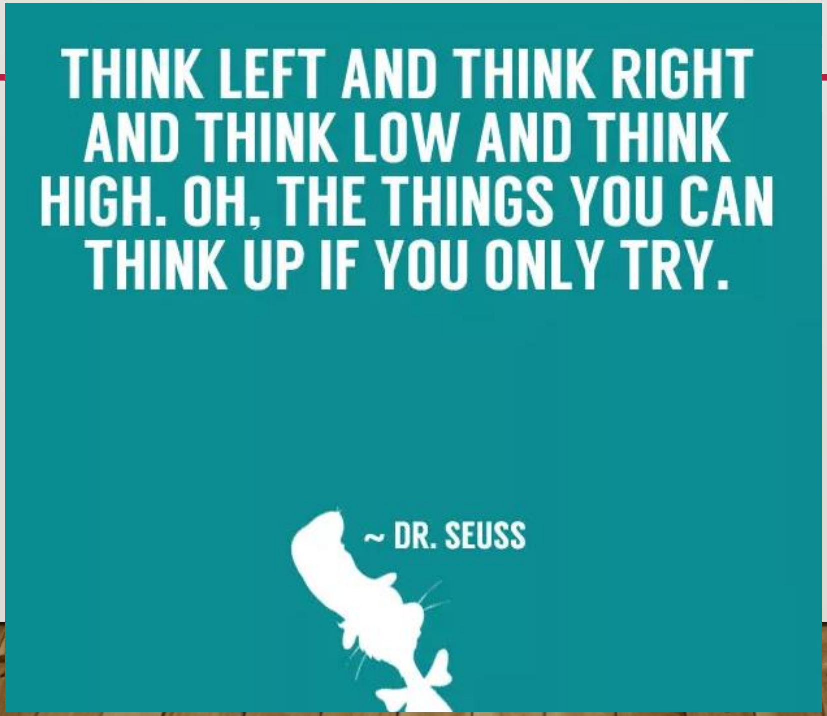
Fix Things Once & For All!

Continuous Improvement (Baseball Style)



Walk the Talk
Satisfying our Customers

Still a long way to go, but we're heading in the right direction!



INVESTMENT CASTING INSTITUTE

Case Study: Plant Modernization – Navigating Challenges & Overcoming Obstacles

Vince Gimeno
O'Fallon Casting

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Panel Discussion

Plant Modernization: Navigating Challenges & Overcoming Obstacles

by
Vince Gimeno
O'Fallon Casting

Abstract
Change is critical for any foundry to compete, thrive and keep up with the times. The only way to experience success in the midst of change is by employers and employees coming together in order to communicate and achieve one common Goal.
The presentation will describe:

1. Leadership and support – Vision of the business and customer confidence.
2. Planning - If the foundry is, starting from an empty lot the preparation and planning are critical. It is very important that the architect/contractor and management review the plans in depth in order to guarantee a successful project. Modernizing an existing foundry needs that same critical preparation and planning. This will allow for production and customer schedules to be maintained.
3. Types of improvement in process
4. Employee Involvement – Is the key for proper implementation and success of the project.
5. Foundry culture- Multiple improvements over several years helps to create a culture of success. This helps make the task easier for the employee and allows them to produce more with less stress and effort.
6. Building support by employees and management- The benefits are numerous when it comes to positive changes. Support from the employees and management together will help achieve success and growth opportunities for the entire company. Make change work for you.

Plant Modernization: Navigating Challenges and Overcoming Obstacles

By: Vince Gimeno

General Manager,

O'FALLON CASTING
NONFERROUS INVESTMENT CASTINGS

Introduction

Change is critical in order for a foundry to compete, thrive and keep up with the times. The only way to experience success in the midst of change is by employers and employees coming together in order to communicate and achieve one common goal.

Topics of Discussion

- Leadership and support
- Planning
    A. Starting from scratch
    B. Modernizing existing foundry
- Types of Improvement In Process
- Employee involvement
- Foundry culture
- Building support by employees and management

Leadership and Support

Vision of the business and customer confidence are key in overcoming the challenges and obstacles that might arise. Commitment from the top down, supporting the transformation.

Planning

If the foundry is starting from an empty lot the preparation and planning are critical. It is very important that the architect/contractor and management review the plans in depth in order to guarantee a successful project.

Planning

Modernizing an existing foundry needs that same critical preparation and planning. This will allow for production and customer schedules to be maintained.

Types of Improvement In process

- Wax Injection Equipment
  a) Automation
  b) Assembly Standardization
- Shell Room
  a) Material Handling
  b) Robotics
- Dewax/Foundry
  a) Mold Handling
  b) Metal Handling

Types of Improvement In process

- Shell Removal
  a) Equipment Available
  b) Design and Build Equipment
- Post Cast Operations
  a) Heat Treat
  b) Straightening
  c) FPI
  d) Radiography
  e) Metrology Inspection
  f) Part Marking
- Ship Best Commercial Way

Employee Involvement

Employee involvement is key for the proper implementation and overall success of the project.

Foundry Culture

Multiple improvements over several years helps to create a culture of success. This helps make the task easier for the employee and allows them to produce more with less stress and effort.

Building Support by Employees and Management

The benefits are numerous when it comes to positive changes. Support from the employees and management together will help achieve success and growth opportunities for the entire company. Make change work for you.

INVESTMENT CASTING INSTITUTE

Fluid Flow Modeling Validation of Complex Geometries

Alan Druschitz
Virginia Tech

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 11

Fluid Flow Modeling Validation of Complex Geometries

Christina Romano*, Jordan Seibert*, Aaron Wong, Alan Druschitz**

*General Motors, Bedford, IN
**Virginia Tech, Blacksburg, VA

Abstract

This paper describes an undergraduate senior design project performed at Virginia Tech. The purpose of this project was to determine the accuracy and limitations of a commercial metal casting simulation software when used for complex, investment castings. Simulation software is a valuable tool in the metal casting industry since it helps to quickly optimize casting processes by virtually modeling the outcome of a desired casting. Simulation and physical casting trials of a complex geometrical shape (turbine blade) were evaluated to more fully understand the capabilities of the software. The simulations illustrated combinations of various parameters: mold pre-heat temperature, metal superheat temperature, and gating system design. Most of the simulations filled completely and uniformly with the exception of the extreme parameter conditions (no mold pre-heat and no metal superheat). The physical castings of the blades, however, did not fill completely, leading to the conclusion that there is some discrepancy between the simulation software and the physical casting capabilities of our foundry.

1. Introduction

Virginia Tech has an on campus foundry that is used for educational labs, undergraduate research, and student design teams. Casting simulation software is often used to assist with foundry projects. In this study, simulation software was used to predict how a mold would fill with regards to thermal and fluid flow parameters before a mold or physical casting was actually made. This allows for efficient testing of new mold designs without wasting time and materials. For these reasons, simulation software is a useful tool for not only our foundry, but the casting industry as a whole. Our foundry does not have all of the capabilities of the industrial foundries, thus, the goal of this project was to discern the accuracies and limitations of our simulation software as it relates to our foundry. This project broadened the understanding of this simulation software for the students involved.

The objectives established to accomplish the goal of this project were to investigate gating systems, metal casting practices, and material properties. Multiple simulations were performed with differing casting conditions (metal superheat temperature, mold pre-heat temperature, and gating system design). Physical castings were then produced based on the investigated conditions and compared with each respective simulation.

1.1 Solidification

Solidification plays a crucial role in the manufacturing of complex turbine blades in order to ensure that the blades do not fail under extreme operating conditions. During solidification, nucleation and growth occur with the formation of nuclei once the liquid metal has cooled just below the equilibrium temperature [1]. The nuclei then grow into one of three types of grain structure; equiaxed, columnar, or singular. When equiaxed grains form, the dendrite tips of the grains are allowed to grow freely during solidification, which results in random grain formations throughout the part [1]. Columnar grains form through directional solidification when heat is extracted from the casting in the opposite direction of grain growth [1]. The grains form parallel to each other in the same direction. Turbine blades today are also made with a single crystal process, which eliminates grain boundaries in the final casting. By eliminating grain boundaries, the probability of cracking and thermal shock stresses are greatly reduced [2]. A single crystal structure also significantly increases the creep strength of the casting since grain boundary sliding is eliminated. This allows the castings to be used in higher temperature applications [2]. However, creating a single crystal structure is not feasible with the capabilities of our foundry. Thus, an equiaxed grain structure was produced in this project.

1.2 Fluidity and Shrinkage

When casting complex shapes, fluidity and shrinkage of the cast metal must be taken into account to create a successful casting. Turbine blades are usually made from nickel-based superalloys due to the extreme environments they perform in, which consists of very high temperatures and mechanical stresses [3]. Fluidity can be determined by casting uniform spirals and observing how well the metal fills the spiral. Shrinkage, on the other hand, can be determined by casting linear rods and comparing the cast dimensions to the original mold dimensions. A study conducted on alloy UNS N07713 concluded that increased fluidity occurs with increased superheating above the melting temperature of the metal and had 2.3% shrinkage upon cooling [3]. It was also stated that as the pouring temperature increased, the amount of shrinkage in the part decreased [3]. Therefore, we varied the superheat of the nickel-based alloy used in study (alloy UNS N06625) to determine which superheat temperature would provide the greatest fluidity, and, consequently, the least shrinkage.

1.3 Gating System Design

An often overlooked engineering challenge in casting is gating design. Gating systems are a series of channels that guide molten metal from the point of pour to the part. The system consists of a pour cup or basin, downsprue, well, runner(s), gate(s), and vent(s). The pour cup is the initial opening to the mold that molten metal is poured into. The downsprue is attached to the pour cup and directs the molten metal to a well, which is used to reduce the turbulent flow of the metal as well as collect any impurities that may be in the molten metal. Impurities are undesirable within the cast part because they negatively affect mechanical properties. Runners are the channels that connect the downsprue to the gates and control the flow of molten metal into the part. Runners are designed to avoid sharp redirections of the metal (90° angles), so the metal does not roll over itself and create turbulent flow. Vents are channels connected to the part that allow entrapped gases or particles, which may cause defects, to escape the mold during pouring.

2. Experimental Methods

Two experimental processes (simulation and actual investment castings) were conducted in parallel with each other in order to accomplish the goals of this project in a timely manner. The steps involved with each of these processes are as follows.

2.1 CAD Modeling

The first step required for simulation/modeling is to create a virtual geometric representation, or a computer-aided design (CAD) model, of the casting of interest using CAD modeling software. The parts and the gating systems were created in separate files, and then assembled into one full system, commonly referred to as a tree assembly. The completed system is the file that is used in the simulation software. Once a model of the tree assembly was created, the file was exported in an .igs format, and imported into the simulation software.

2.2 Simulation

After the CAD file was successfully imported into the simulation software, the file was meshed so that the simulation software can interpret the geometry of the part. During meshing, nodes are created on the surface and cross-sections of the tree assembly. These nodes are what the simulation software uses to calculate information on fluid flow and solidification. After meshing, the casting parameters are set to the desired values, Table I. There were three gating designs and four simple design shapes for this project. Each gating system design required nine combinations of the parameters of interest. Simulations were also run with extreme conditions involving no mold pre-heat and no metal superheat. The extreme conditions could not be physically cast, so they were only run as simulations. Since it is known that a casting made under these conditions would be nearly impossible, these simulations were used as a way to evaluate the simulation software and make sure that it would not predict impossible conditions as successful.

Table I: Casting simulation parameters for each gating design.

Parameter	High	Low	None
Mold Pre-Heat Temperature	2000 °F	1550 °F	72 °F
Metal Pour Temperature	2950 °F	2650 °F	2460 °F

2.3 Physical Casting Process

The physical casting process can be broken down into two main parts; investment mold making and casting, which are described in detail below.

2.3.1 Investment Mold Making

The investment mold making process started by making a silicone rubber mold from a pattern of a small, machined, turbine blade. Once the rubber mold was completed, the inside of the mold was pre-heated using a heat gun and filled with liquid wax. The mold was lightly tapped to remove any trapped air bubbles. After 20-45 minutes, the wax was completely solid. Once the blades were made in wax, they were attached to wax gating systems to create wax tree assemblies. The first parameter varied was the gating system design. The tree assemblies for the simple shapes used in the project were 3D printed as a single part. These tree assemblies were coated in alternating layers of ceramic slurry and stucco. Investment molds are usually made of nine layers in our foundry. For this study, the wax tree assemblies were given a total of ten layers, and the 3D printed polymer tree assemblies were given a total of eleven layers of slurry and stucco. The extra layers were added to reinforce the mold, and prevent cracking during burnout. Burnout is when the wax or plastic is melted out of the mold to leave a hollow shell. The overall process is illustrated in Figure 1.

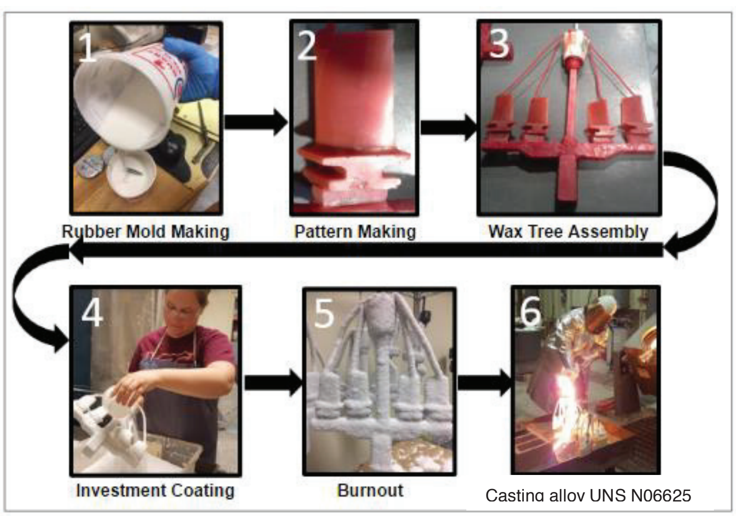


Figure 1. Process flow for producing an investment casting.

2.3.2 Complex Geometry Castings

After creating the investment shell, the mold was cast in the desired metal. For this project the metal was alloy UNS N06625. The other two parameters that changed throughout the experiment were the mold pre-heat temperature and the metal superheat temperature. The high mold pre-heat temperature was 2000°F and the low temperature was 1550°F. The metal superheat temperature is the pouring temperature minus the liquidus temperature. The high superheat condition was 450°F ± 15°F and the low superheat condition was 230°F ± 20°F. Each gating design had four molds; two were pre-heated with the high pre-heat temperature and the other two were pre-heated at the low temperature. The metal was melted in an induction furnace and the temperature of the metal was determined using an immersion thermocouple. Once the metal was within the desired superheat range, a mold was taken out of each of the pre-heat furnaces, held under the spout of the induction furnace, and the metal poured directly out of the furnace into the mold to minimize temperature loss. This was done twelve times so that all the different combinations of the parameters were cast. The actual casting conditions are listed in Table II.

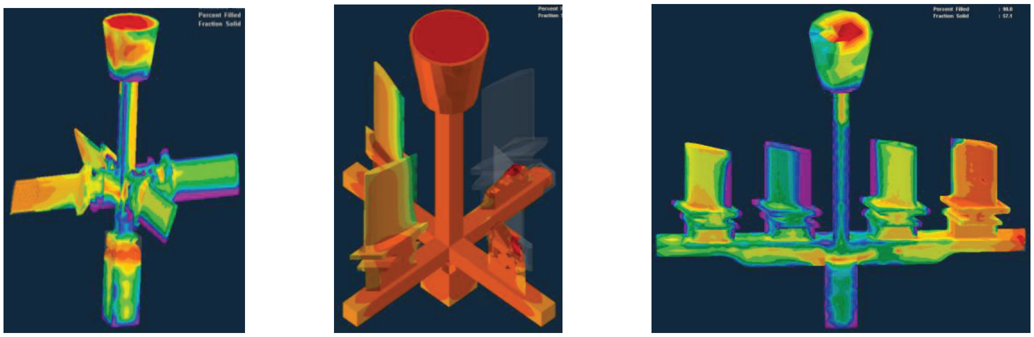
Table II: Actual casting conditions.

	Gating Design A	**Gating Design B**	**Gating Design C**
Mold Pre-Heat	**Metal Superheat**		
2000 °F	252 °F	210 °F	220 °F
	465 °F	440 °F	460 °F
1550 °F	210 °F	252 °F	220 °F
	460 °F	440 °F	465 °F

3. Results and Discussion

3.1 Simulation Results

Almost all of the simulations showed complete filling for each gating system design. The only exception where incomplete filling was indicated were the no mold pre-heat temperature combined with the no metal superheat temperature condition for each of the gating system designs. This extreme condition, where the mold was at room temperature and the metal was set to the liquidus temperature of alloy UNS N06625 (2460°F), influenced the solidification and fluid flow patterns in a variety of ways for the different gating system designs. Gating System A, Figure 2(a), only had one small void in the top portion of one out of the four blades. This simulation also showed the thin areas of the blades (facing downwards) filled first followed by the thicker side of the blade. It can be inferred that fluid flow modeling was influenced by gravity since all of the simulations showed metal flowing from the bottom of the mold to the top. Gating System B, Figure 2(b), had substantial filling of two out of the four blades with metal barely reaching the bases of the remaining two blades. The thin edges of the two blades that partially filled displayed ripples of where liquid metal had not quite reached the very edge of the blades. The lack of filling of the blades as well as the thin areas indicated that the metal froze prematurely, reaching the solidus temperature, before metal was able to completely fill the blades. Gating System C, Figure 2(c), also had a small void in the middle of one out of the four blades, however, this simulation indicated that liquid metal was able to flow through a seemingly solid downsprue to reach the blades. The no pre-heat, no superheat simulation for Gating System C illustrated slow filling of the downsprue and well at the start with the downsprue beginning to solidify as the runners filled with liquid metal. With one blade left to fill, liquid metal flowed through the almost solid runners to enter the gate of the final outer blade. It was seen that the last outer blade was filled with metal at the liquidus temperature while the downsprue and runners already contained solidified metal. The right outer blade filling with metal even though the downsprue and runners were already nearing the solidification temperature would be rather unlikely as the incoming metal would have already been significantly cooled.



(a) (b) (c)

Figure 2. No pre-heat, no superheat simulation of Gating System A, Gating System B, and Gating System C, respectively (left to right).

The no pre-heat and no superheat parameters were known to be a near impossible filling condition based on the properties of the materials involved (ceramic shell and alloy UNS N06625) as well as the knowledge of how metal cools as it is being poured. Additionally, the induction furnace is turned off for safety reasons just before pouring, causing the metal to begin to cool. The simulation software does not account for the metal cooling as it is being poured; it only depicts a constant flow of uniform temperature metal.

The remaining simulation trials depicted successful, uniform filling of all the blades within each gating system design. For Gating Systems B and C, liquid metal would fill the entire cross sectional area of the blade (filling both the thin and thick area at the same time) and flow upwards at this same rate until complete. The simulation for Gating System A indicated that the liquid metal would flow with respect to gravity, such that the thin edges of the blades would fill first since they were facing downwards. However, liquid metal tends to fill thicker areas first since these areas are more open. It was also hypothesized that the surface tension of the metal would play a key role in the ability to successfully fill thin sections.

Upon further evaluation of the simulation software, it was found that the material databases did not contain surface tension values for any of the metals investigated. Thus, an additional experimental simulation was conducted in order to determine if an inputted surface tension value for alloy UNS N06625 would influence the simulation results. The parameters chosen for the simulation were no mold pre-heat temperature and no metal superheat temperature in order to more easily gauge any differences between the two simulations since this was the only condition where there was unsuccessful filling of the blades. Figure 3 shows the simulations of Gating System A with a surface tension value found in literature (1.35 N/m) [4] and without a surface tension value. No significant difference was observed between these simulations. Therefore, this study did not show any significant effect on mold filling due to surface tension.

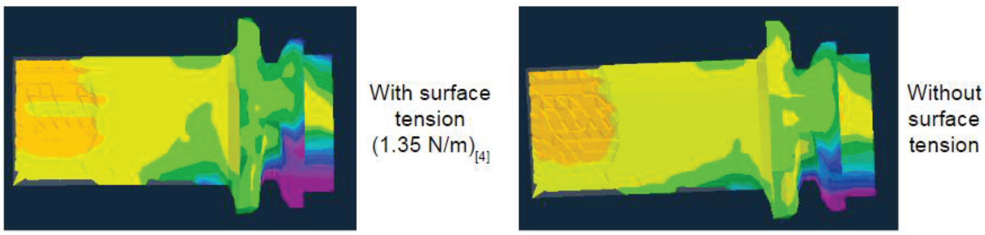
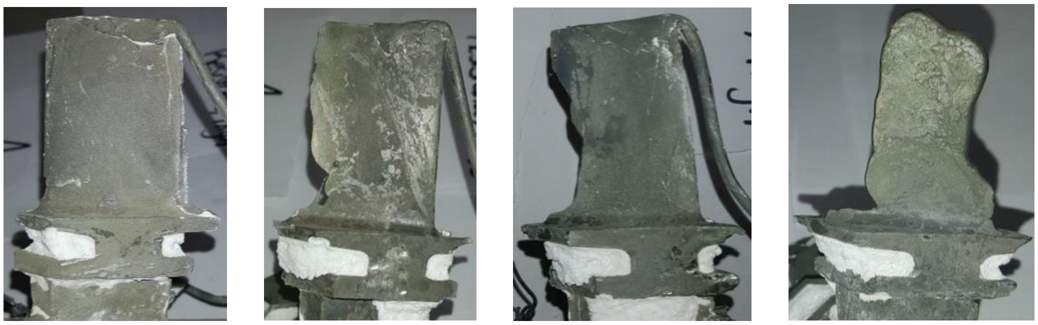


Figure 3. No pre-heat, no superheat simulation of Gating System A with (left) and without (right) surface tension values.

3.2 Physical Casting Results

Physical castings of each turbine blade simulation were performed. The actual castings were compared to the simulations in order to determine the accuracy and limitations of the simulation software. Gating System A was the only system to have one of the trials fill all four turbine blades completely, which was under the high pre-heat and high superheat parameters. As both the pre-heat temperature and the superheat temperature decreased, less of the blades filled for Gating System A. The progression of decreasing parameters (decreasing temperatures) is shown in Figure 4. Opposite to what the simulations illustrated, the thin edges of the blades (facing downwards) did not fill first since the thin sections did not fill completely in three out of four trials.



(a) **(b)** **(c)** **(d)**

Figure 4. Gating System A: (a) high pre-heat and high superheat, (b) high pre-heat and low superheat, (c) low pre-heat and high superheat, (d) low pre-heat and low superheat.

The blades of Gating System B did not fill completely for any of the trial parameters, Figure 5. The trials with high metal superheat had more complete filling, minus the thin edges, than those with lower superheat temperatures. Generally, the more liquid metals are superheated above the liquidus temperature, the more fluid the metal becomes. The liquid metal can than more easily fill thin areas of a mold before solidifying since it will take more time to reach the solidus temperature. This gating system design was one of the bottom-fill designs, such that the blades fill from the base upwards. Bottom-fill designs promote uniform filling, however non-uniform filling was evident as flow lines were visible on the blades, Figure 5(b). The non-uniform filling indicated that the metal first filled the thicker edge of the turbine blade and then the thinner area of the blade, but, the metal solidified before reaching the very thin outer edge. This pattern of flow lines was repeated along the entire length of the blades.

(a) **(b)** **(c)** **(d)**

Figure 5. Gating System B: (a) high pre-heat and high superheat, (b) high pre-heat and low superheat, (c) low pre-heat and high superheat, (d) low pre-heat and low superheat.

For Gating System C, all of the blades did not fill completely. This gating system was designed to be a more calculated approach to gating design, such that the design included proper tapering of the runner, a 1:4:4 ratio of the cross-sectional area of the downsprue to the total cross-sectional area of the runners to the total cross-sectional area of all the in-gates, plus rounded edges to promote uniform filling. Even with the efforts towards promoting uniform filling, this gating system design contained the greatest amount of non-uniform filling. This set of blades also exhibited the same general fill pattern as Gating Design A; as pre-heat and superheat temperatures decreased, the amount of filling also decreased, Figure 6.

(a) **(b)** **(c)** **(d)**

Figure 6. Gating System C: (a) high pre-heat and high superheat, (b) high pre-heat and low superheat, (c) low pre-heat and high superheat, (d) low pre-heat and low superheat.

3.3 Additional Experimental Results

A necessary step towards identifying the capabilities of the simulation software was identifying whether the software could be used to simulate simple shapes using the parameters used for the turbine blade. For the simple shape trials, four simple shapes, a sphere, a cylinder, a rectangular prism, and a pyramid were chosen. The sphere was chosen because of its lack of edges and corners, which promotes more uniform filling. The cylinder was chosen for similar reasons as the sphere, but also introduced edges. The rectangular prism was chosen to confirm that the limited thickness of the blade could be modeled accurately. And lastly, the pyramid was chosen to show whether alloy UNS N06625 has sufficient fluidity to fill thin sections, a problematic dimension in casting the turbine blades.

4. Conclusions

The comparisons between the physical castings and the simulations indicated that the simulations were not accurate. The evidence of non-uniform filling indicated that the uniform filling predicted by the simulations was incorrect. Out of the three designs, gating design A was the only design to match the simulations when the mold was cast with a high superheat and high pre-heat.

4.1 Simple Shapes

For the simple shape trials, both the physical castings and simulations of the simple shapes completely filled. This indicated that the simulation software can accurately predict the filling of simple shapes and may indicate that the software has difficulties with complex, thin section size geometries.

4.2 Turbine Blade Orientation

Inverting the orientation of the turbine blades, such that the thick section was down and the thin section was up, showed that the blades would fill successfully. The assumption that the metal would prefer to fill thick section first was therefore correct.

5. Future Work

In the future, this project could be expanded by obtaining an industry level license for simulation software, comparing the simulation results of this software to other modeling software, performing multiple trials of each design under identical casting parameters, plus determining the heat transfer coefficient of the ceramic investment shell and surface tension values of the alloy used to insure accurate inputs.

5.1 Industry-Level Licensing

Currently, we have a student-level software license. An industry-level software license would allow for access to a larger more in-depth materials database and a materials database generator.

5.2 Other Software

There are many simulation software choices for castings. Comparing simulations produced using a variety of software packages would be valuable.

5.3 Multiple Trials

All of the trials performed for this project were only performed once. To improve statistical significance and to establish a trend or correlation, a minimum of three trials would be necessary.

5.4 Heat Transfer Coefficients and Surface Tension Values

A potential oversight in the modeling procedure was the assumption that the default values provided for the heat transfer coefficient and surface tension were accurate. A large difference between the provided values and the real values would create an error in the simulation. Experiments like the sessile drop test and the addition of thermocouples to the molds, would provide measured information that would allow the accurate calculation of the surface tension and heat transfer coefficient values respectively.

6. Acknowledgements

The authors would like to thank to James Sturgeon (Conbraco) for donating the UNS N06625 nickel alloy used in this research.

7. References

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INVESTMENT CASTING INSTITUTE

An Introduction to Self-Monitoring, Adaptive Recalculating Treatment Technology (SMARTT) in Degassing Aluminum

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Foseco

64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

Paper № 12

FOSECO

An Introduction to Self-Monitoring Adaptive Recalculating Treatment Technology (SMARTT) in Degassing Aluminum.

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Introduction

The production of Aluminum castings globally is dominated by the automotive industry and the growing importance of emissions and fuel economy has resulted in a rapid increase in the use of Aluminum castings. For these demanding applications, many of the attributes in terms of mechanical strength, elongation and fatigue strength can no longer be satisfied by standard alloys and so new alloys with greater potential have been, and will continue to be, developed. To exploit the potential of these alloys completely then pore-free castings of high cleanliness and fine structure must be produced. Safety critical castings now require elongation in excess of 10% from the casting itself and this is moving close to the limit for the alloy. The "window" for melt properties to fulfill these requirements becomes smaller and smaller whilst the starting conditions such as ingot quality, melting and holding furnace condition, temperature control and melt transfer can become limiting factors. To ensure that the correct casting quality is achieved then a more effective and technically sound melt treatment is essential followed by a well-designed and controlled pouring practice.

Another important attribute required by the automotive industry is reproducibility and so any melt treatment adopted must be capable of achieving consistent levels of cleanliness and hydrogen control. Many quality management systems also require a 100% record of production data so again a sophisticated melt treatment system with data storage becomes more attractive to the automotive industry.

An innovative process which can automatically achieve the same melt quality regardless of the external environmental conditions will be the key to the future production of truly high quality castings meeting the needs of this growing market segment.

Degassing Simulation

Foseco's non-ferrous Marketing and Technology team have worked with tsc - Technology Strategy Consultants to develop a web-based batch degassing model. It has been designed a s a tool to analyze quickly foundries' operations, and make suggestions for their improvement. The mathematical model behind this software is based on the best available published information concerning the kinetics of hydrogen degassing (e.g. hydrogen solubility, diffusivity, mass transfer rates and stable bubble sizes). An extensive trial program was undertaken to provide specific information about individual rotors under different conditions.

To characterize different rotors the following trials were carried out[1]:

- Power analysis of degasser rotors
- Mixing capabilities of degasser rotors
- Gas solubility tests in water
- Foundry trials in aluminum melts

Parameters Influencing Degassing Results

Three main groups of variables influence the degassing efficiency: ambient conditions, rotary degasser parameters, and melt properties. The hydrogen concentration in the melt has been calculated using the Degassing Simulation for the following widely common set of parameters (**Table 1**); and variations of the parameters illustrate the influence on the degassing result and the final hydrogen content in the melt after treatment.

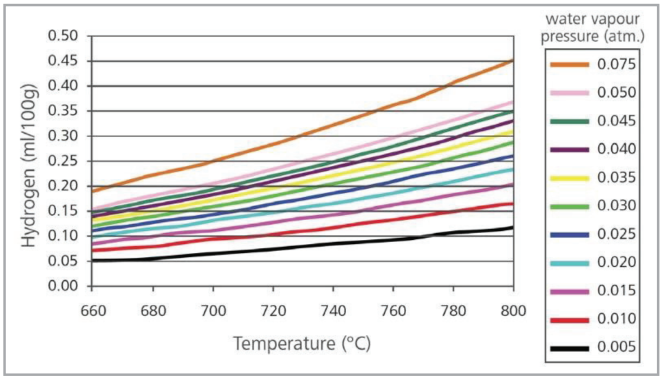
ATL 1000 with 850 kg melt	**XSR 220 rotor**
AlSi7Mg	420 rpm
750ºC melt temperature	20 l/min inert gas
50% relative humidity	0.30 ml H_2/100g Al starting level
25ºC outside temperature	

Table 1Model simulation parameters

[1] A full description of the development work is given in Foundry Practice 256 (2011).

1. Ambient Conditions

The melt forms an equilibrium with the water in the surrounding atmosphere; a warm and humid climate gives much higher hydrogen content in the melt than a dry and cold climate (**Picture 1**).



Picture 1 Influence of ambient conditions on hydrogen equilibrium (0.005 atm = 5°C / 50% rH; 0.050 atm = 35°C / 90% rH)

During rotary degassing the melt is in interaction with the atmosphere and picks up hydrogen again. The degassing simulation shows the effect of different ambient conditions (**Diagram 1**):

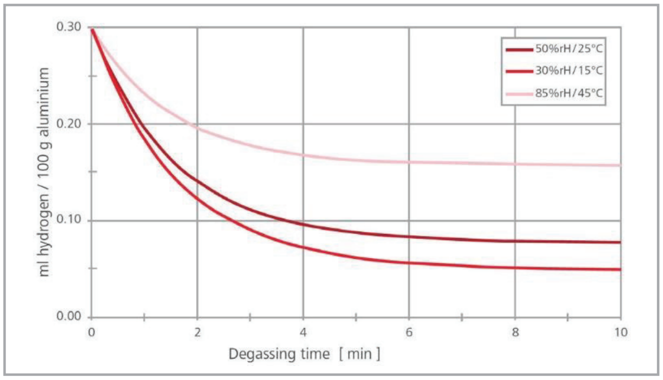


Diagram 1: Degassing curves for different ambient conditions

2. Rotary Degasser Parameters

The rotary degasser can run a treatment with different rotation speed and inert gas flow rates. Each rotor design has minimum and maximum values for those parameters – working conditions – for rotor speed and inert gas flow rate. It is important that both parameters are within the limits; running a treatment at very high rotation speed and extensive flow rates would create too much turbulences or in extreme cases an aeration of the rotor with a complete loss of degassing performance.

The **Diagrams 2** and **3** show degassing behavior for typical parameters of an XSR 220 rotor under varying conditions:

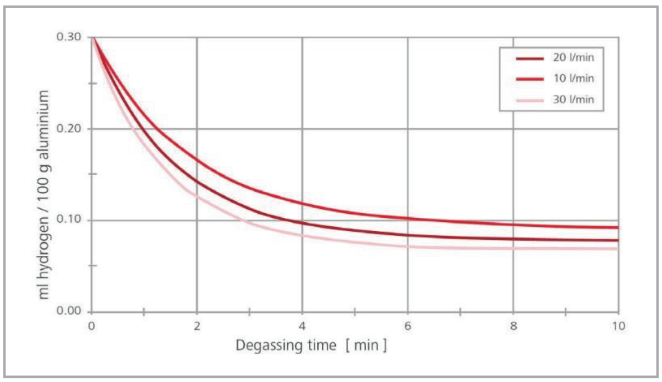


Diagram 2: Degassing curve for inert gas flow variations

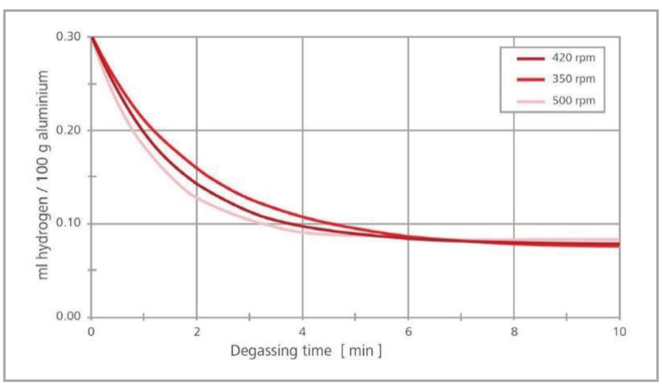


Diagram 3: Degassing curves for rotor speed variations

3. Melt Properties Before Treatment

The alloys composition has a huge influence on the degassing performance. Elements like Magnesium increase hydrogen solubility while Silicon or Copper slightly decrease it (**Diagram 4**). The melt temperature influences the equilibrium with the atmosphere; melt at higher temperature dissolves more hydrogen (**Diagram 5**).

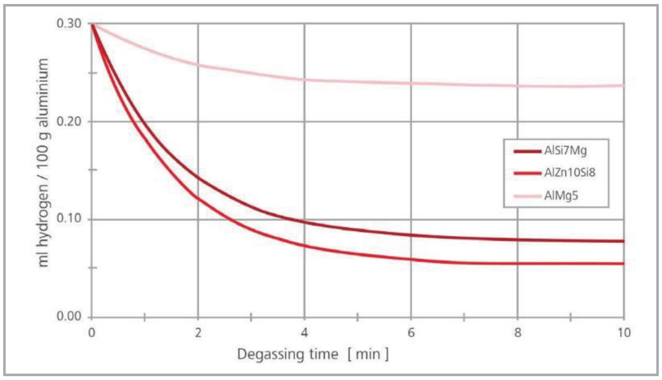


Diagram 4: Degassing curves for different alloys

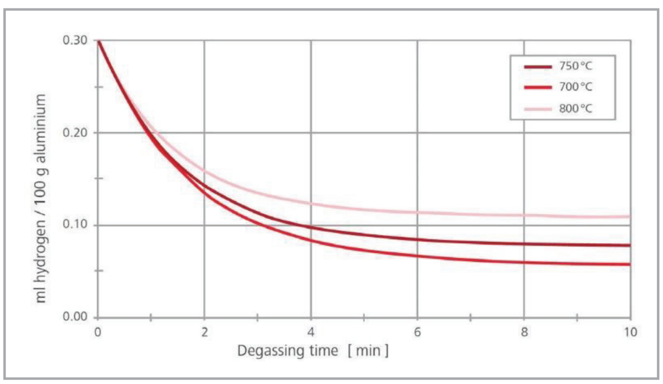


Diagram 5 Degassing curves for different melt temperatures

The starting hydrogen level is often unknown, but the diagram shows that variations in the initial hydrogen does not change the result (**Diagram 6**).

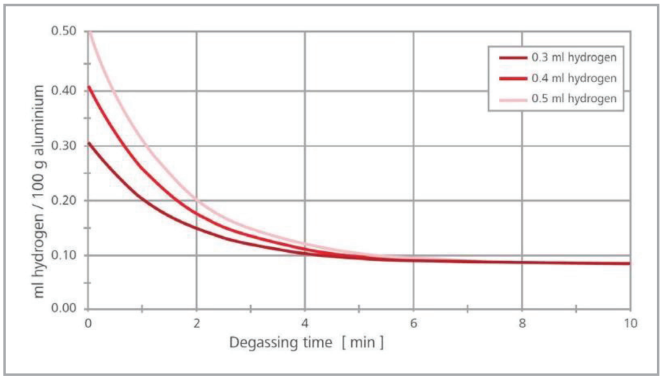
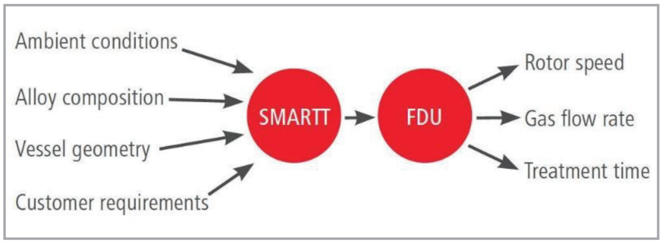


Diagram 6: Degassing curves for different initial hydrogen levels

SMARTT – An Innovative Process Control

SMARTT is the acronym for self-monitoring adaptive recalculation treatment and an innovative process control that analyses all incoming parameters and calculates the treatment parameters for the rotary degassing process just before each treatment. The target for the optimization is a constant melt quality after each treatment.

The SMARTT software is installed on a Windows PC, input and output of data is carried out on a comfortable touch screen panel. The SMARTT PC is LAN connected to the Siemens PLC that controls the degassing unit.



Picture 2 Schematic setting of SMARTT

Picture 3: Touch screen interface in a FDU control cabinet door

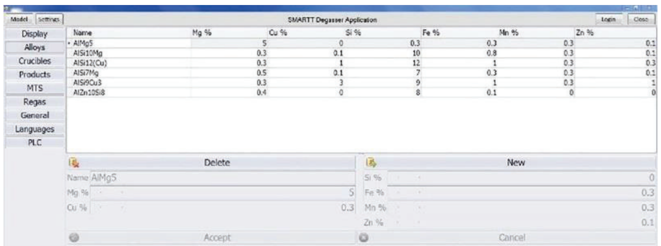
The SQL data base system makes it to an open interface and enables the operator to define a nearly unlimited number of crucible or ladle shapes, alloy types and treatment programs the target for all simulations is the hydrogen content in the melt and used for both degassing and upgassing procedures.

1. Ambient Conditions

Relative humidity and outside temperature are measured by a standard sensor, mounted next to the control cabinet in the area where the treatment takes place. The actual readings are on-time transferred to SMARTT and recorded over time.

2. Alloy Composition and Vessel Geometry

SMARTT comes with a number of pre-defined alloys and crucible or transfer ladle geometries. The user can easily modify, add or delete these. Alloy and treatment vessel become part of each program together with a recommended rotor type and diameter (**Picture 4**).



Picture 4: Alloy screen

SMARTT offers four different treatment schemes to choose from. The calculation is based on a minimum and maximum gas flow rate and rotor speed depending on rotor type and diameter as well as on vessel size. The minimum degassing time is a parameter to ensure proper oxide removal.

High-speed degassing – shortest possible treatment time at highest possible rotor speed and inert gas flow rate. A minimum treatment time is observed to allow homogenization and oxide removal.

Low gas degassing – runs the treatment for a given time at lowest gas consumption and correlative rotor speed to achieve the target.

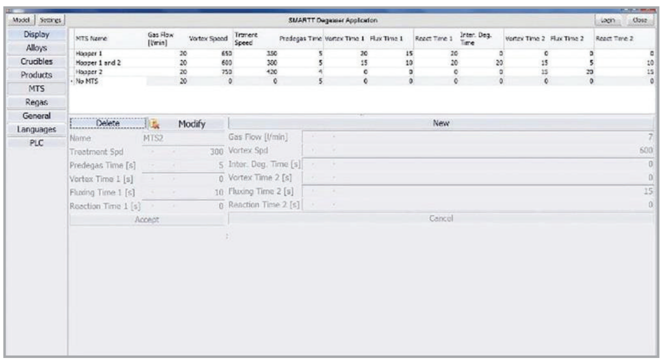
Long life – runs at lowest possible rotation speed to reduce the shaft and rotor abrasion. The corresponding inert gas flow depends on the total treatment time.

Standard degassing – the average of low gas and low speed provides a balance between the two extreme schemes.

The *high-speed* scheme is used if the degassing process is the bottleneck in the foundry and huge amounts of melt are needed for the following casting steps. The *high-speed* treatment can be used for certain time i.e. during morning shift with high melt demand or if the castings are heavy at short cycle time. The other schemes are depending on the local requirements.

4. MTS 1500 Settings

SMARTT is suitable for degassing machines with the optional MTS 1500 automated treatment agent addition as well. The MTS (acronym for Metal Treatment Station) parameter setting is carried out on the touch screen in the conventional way, those parameters are not part of the optimization. Nevertheless, the different MTS programs are part of the treatment programs and combined with optimization schemes and hydrogen targets (**Picture 5**).



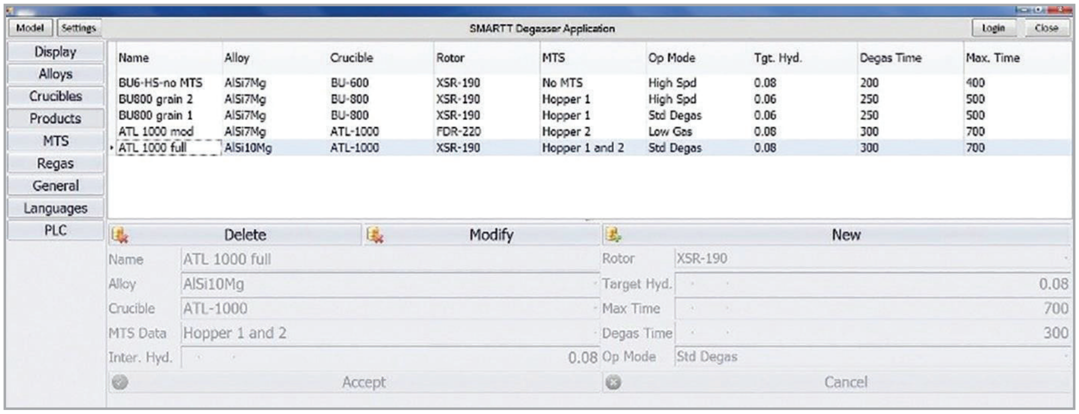
Picture 5: MTS parameter setting screen

5. Product Screen

The product menu brings all pre-defined program parameters together: treatment vessel geometry, alloy and treatment agents. Additionally, the limits for the degassing time are defined. The required hydrogen content in the melt is the target for the optimization process (**Picture 6**).

The different optimization schemes enable the foundry to achieve the same degassing result in the same time using different parameter settings. The low gas options should be used for regions with high inert gas costs; the long-life option reduces the erosion of shaft and rotor while standard degassing is a good balance between the two extremes. High- speed degassing is an option where the degassing procedure is the bottleneck in the melt shop.

A product name differentiates the different settings and makes it easy for the operator to choose the right one.



Picture 6: Product screen

6. Operator Screen

All previously described screens are accessible for the administrator only. The operator sees a specially designed interface to make an easy choice from 10 different administrator defined products. Additionally, the ambient conditions and remaining treatment

Picture 7: Operator screen

Results from Field Trials

The SMARTT software is installed on mobile degassing units with a 1 hopper MTS 1500 dosing system. The trials were started with a simple degassing procedure; the target was to achieve a standard melt quality with a minimum hydrogen level of 0.08 ml hydrogen per 100 g aluminum.

The parameters in **Table 2** - similar to the model simulation in the beginning of this paper (**Table 1**) - were used for the SMARTT trials:

ATL 1000 with 850 kg melt	XSR 220 rotor
AlSi7Mg	0.30 ml H2 / 100 g Al starting level
750° C melt temperature (*)	300 s minimum treatment time (*)
50% relative humidity (*)	25° C outside temperature (*)

Table 2: SMARTT Simulation Parameters, (*) - might vary for some examples

The tables compare the optimized SMARTT treatment parameters to reach the target under varying conditions and parameters. **Table 3** illustrates the different optimization schemes, **Table 4** compares the parameters for three different ambient conditions and **Table 5** provides parameters for different melt temperatures before treatment.

1. Optimization Schemes

The *standard degassing*, *low gas* and *long life* start their optimization procedure at given minimum treatment time and try to find a logical result to reach the target. If no result is found the treatment time is increased. The *low gas* option runs with maximum rotor speed and according inert gas flow to reach the hydrogen target in time while the *long life* option is following the opposite strategy with lowest possible rotor speed and inert gas at maximum limit. The *standard degassing* scheme takes a result just between the two extremes. *High speed* degassing runs the treatment close to the maximum for both rotor speed and inert gas flow and calculates the shortest possible treatment time to reach the hydrogen level after the treatment (**Table 3**).

The *low gas* option consumes 55 liters of inert gas less per treatment compared to the *long life* scheme. Foundries with 4 treatments per hour can save up to 1,500 Nm^3 per year. This is an equivalent to more than 150 gas cylinders.

The reduced speed causes a reduced graphite shaft wearing. Based on customers experiences the life time of shaft and rotor increases by 25 % at 150 rpm lower speed. Depending on treatment conditions a foundry with 4 treatments an hour can save up to 15 sets of consumables – rotor and shaft – per year.

Optimised	Rotor Speed (RPM)	500	500
	Gas Flow (std. l/m)	29	29
Melt: 750	Process Time (s)	300	300
Low gas consumption			
Optimised	Rotor Speed (RPM)	426	426
	Gas Flow (std. l/m)	32	32
Melt: 750	Process Time (s)	300	300
Standard degassing			
Optimised	Rotor Speed (RPM)	353	353
	Gas Flow (std. l/m)	40	40
Melt: 750	Process Time (s)	300	300
Long life for consumables			
Optimised	Rotor Speed (RPM)	500	500
	Gas Flow (std. l/m)	45	45
Melt: 750	Process Time (s)	155	155
High-speed degassing			

Table 3: Results for different optimization schemes

2. Ambient Conditions

SMARTT takes the ambient conditions just before each treatment and starts the optimization procedure based on the product settings. At higher humidity levels in the atmosphere the rotor speed and gas flow rate increase for standard degassing and vice versus. This is an expected result due to interactions of the melt surface with the atmosphere. The SMARTT software finds results up to ambient conditions of 75% rH and 82°F (28°C), for higher humidity levels the 0.08 ml hydrogen target is not achievable due to the regassing on the turbulent melt surface during the treatment.

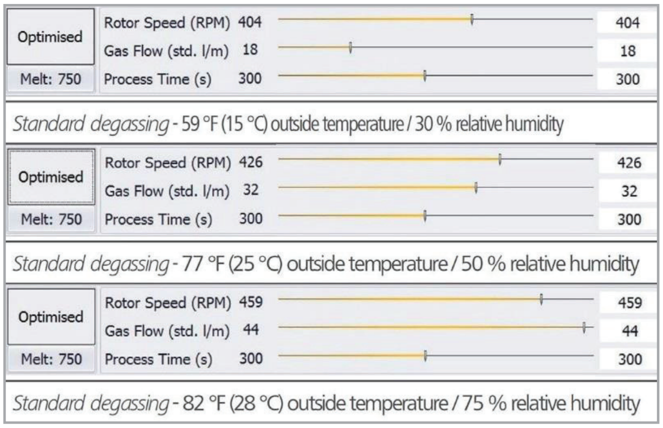


Table 4: Results for different ambient conditions

3. Melt Temperature

Aluminum dissolves more hydrogen at higher temperatures and takes even more hydrogen back at the melt surface from atmosphere. The treatment is carried out at faster rotor speed and higher inert gas flow rates with increasing temperature and conversely. The SMARTT found a logical solution for up to 1436°F (780°C), no parameter setting could be predicted for 1472°F (800°C) due to too high initial hydrogen content and the re-pick-up on the surface (**Table 5**).

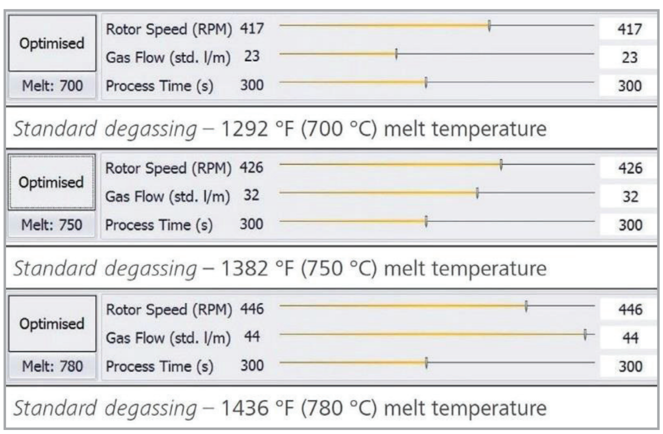
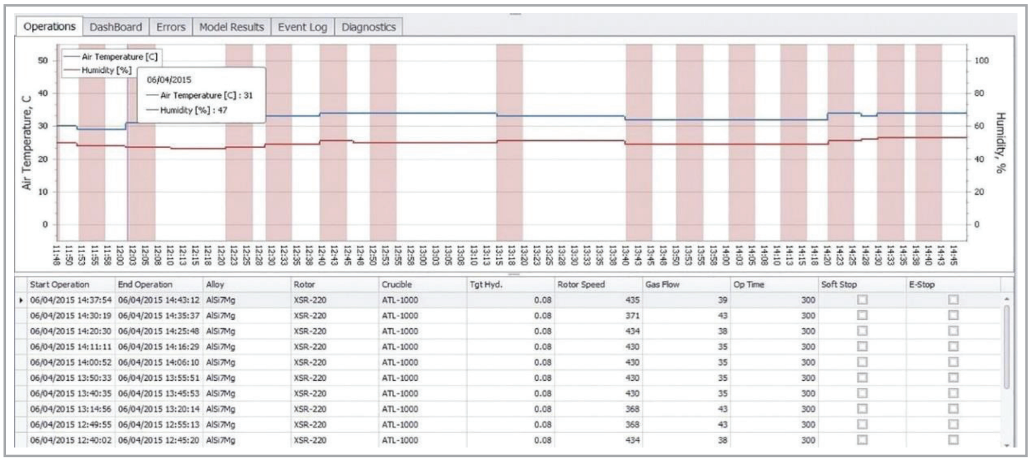


Table 5: Results for different optimization schemes

4. Data Logging

The SMARTT software runs a data logging system that enables a complete parameter tracking for date time and all pre-defined and optimized degassing functions. This very comfortable function replaces complex systems that run on external computers using 3rd party data logging software. The treatment data can be exported to standard office applications for further analysis.



Picture 8: Data logging screen

Summary

- Casting requires a melt on a constant hydrogen level.
- Inconsistent starting conditions in a foundry make it impossible to always reach this in the cost-effective way.
- Foundries today compensate this effect in mostly overrunning the treatment which wastes inert gas and graphite consumables.
- SMARTT offers a comfortable interface to program all necessary treatment steps.
- The innovative degassing control predicts the best treatment parameters for different schemes under given conditions.
- SMARTT saves inert gas or extends graphite consumables lifetime.
- SMARTT records all treatment parameters.
- An innovative process control is the best solution for foundries that treat high melt volumes with a number of different castings that require the same or similar quality levels.

INVESTMENT CASTING INSTITUTE

Using Computer Simulation to Drive the Design of Feeding Systems for Investment Castings

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64TH TECHNICAL CONFERENCE & EQUIPMENT EXPO 2017

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Using Computer Simulation to Drive the Design of Feeding Systems for Investment Castings

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Abstract

Investment foundries use a variety of methods for design of feeding systems. Many of these methods are based on non-scientific principles, or principles which neglect the actual behavior of the cast metal during solidification. There is now a set of tools and principles available which, if applied correctly, will reduce or eliminate the vast majority of feeding problems encountered in investment casting. Application of these techniques to a given casting may often require only 20 or 30 minutes of human and computer time, yet this may eliminate years of problems in subsequent production of the castings. Considerable cost savings in terms of reduction of scrap and customer returns can be realized. This paper will explain the principles and the use of computerized tools, as well as present an example where these methods have been successfully applied in an actual foundry to improve quality and reduce defects.

Introduction

Correct design of feeding components for investment castings is essential for a foundry to be successful in the production of high-quality castings. In today's environment where customers demand that the lead time for new parts be as short as possible, foundries who can produce sound castings from the very start have a distinct advantage; proper rigging system design is the key to making this happen.

Design of efficient gating/feeding systems for investment castings has been difficult for foundry engineers due to a number of factors. Chief among these is the complex geometry of many commercial castings; while there have been well-established design rules for a number of years, the application of these rules to a variety of commercial casting shapes typically involves cumbersome calculations that, when performed manually, require a number of simplifications to reality. These approximations can reduce the accuracy of the resulting designs. Even when rigging calculation methods are used, if the work is not integrated with a simulation tool, extra effort is needed to perform the calculations and the data used is not nearly accurate as simulation results themselves, which take into account such things as casting alloy, mold materials and the like.

With the advent of sophisticated software simulation systems in recent years, it has become possible to synthesize a number of the elements of good rigging design into a general method that is fast, thorough and highly accurate. This method overcomes many of the difficulties listed above. In addition, because of the automation involved, this method allows foundry personnel who may have limited experience (e.g., new foundry engineers) to effectively design casting process methods. In the past, some foundries have experienced major problems when experienced designers retired from the workforce; an automated design method lessens the impact of such an occurrence.

The Design Process

The general design process consists of the following steps:

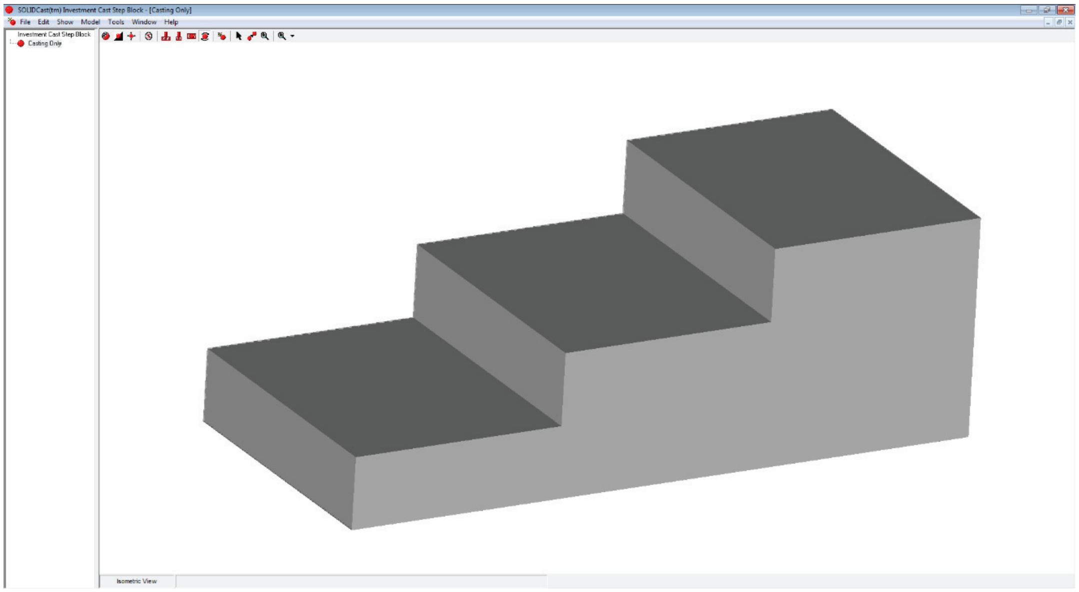
- Simulation of the ‘Naked’ Casting
- Gate Sizing and Feeding Design
- Rigging Geometry Creation
- Verification via CFD/Solidification Simulation

The balance of this paper will illustrate these steps and provide a foundry case study of rigging design.

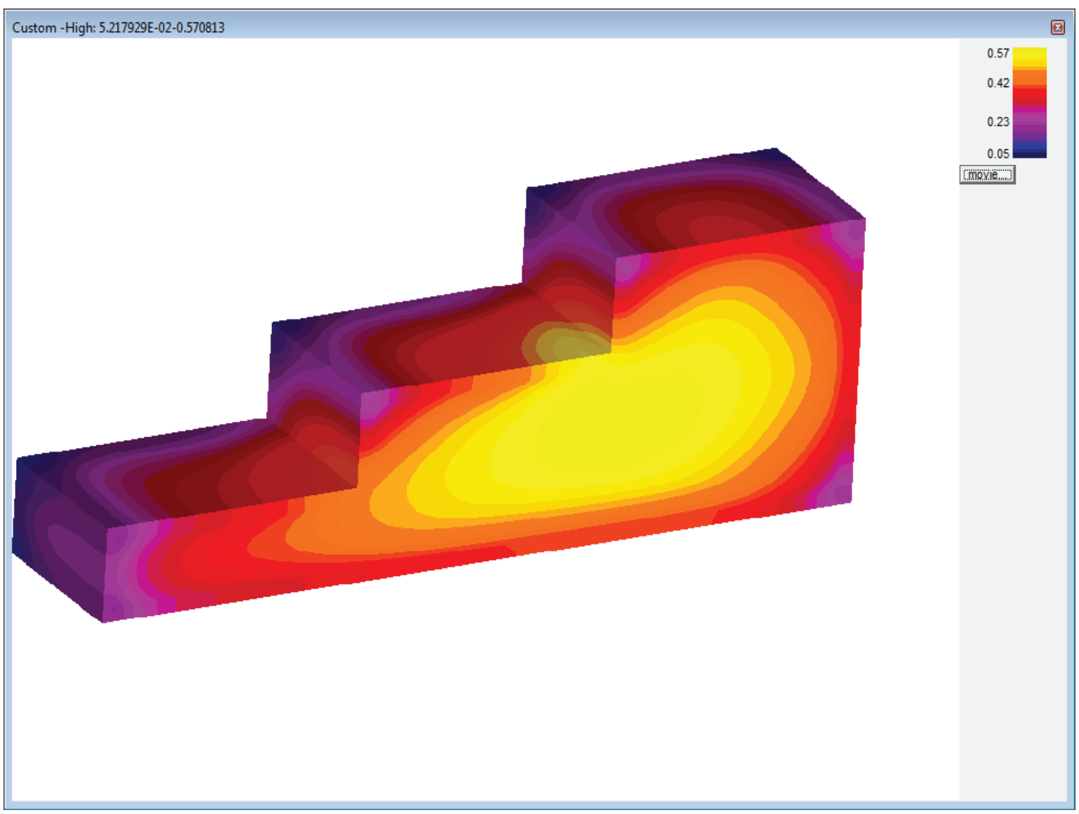
“Naked” Simulation

The first step in the rigging process is to run a simulation of the part ‘naked’; that is, without any rigging system. Simulation results show the effects of the part geometry on the overall solidification. In this initial simulation, filling analysis is typically not done, which provides extremely rapid results, and can point out preferred gate locations which would promote directional solidification.

All that is required for the initial simulation is a casting model, normally provided by the customer in STL file format, and basic process details such as casting alloy, shell material, pouring temperature and shell pre-heat temperature.



STL model of a step block casting.



'Naked' simulation results, without filling.

Gate and Feeder Bar Design

Once the initial simulation is complete, the data from the simulation can be used to design the rigging components. The gates are typically designed first, followed by the feeder bar. The software uses the progression of solidification, along with a pattern recognition algorithm, to determine the separate feeding paths on the casting. Further, the software can find the last points to freeze on each feeding path, which will be the preferred gate contact points.

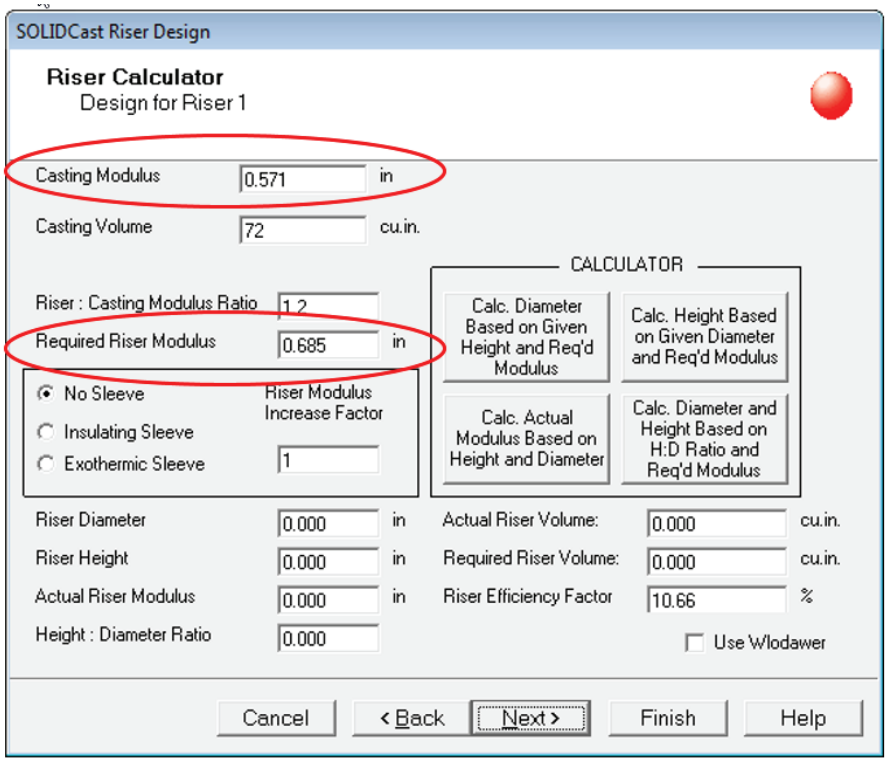
Gate and Feeder Bar sizes for each feeding zone are calculated by the software using variations on the well-known Modulus Technique. While the Modulus is a geometric calculation (Volume/Surface Area), solidification time information from the initial simulation is converted into a ‘Thermal Modulus’. This takes into account not only casting alloy and shell material, but also the solidification dynamics of the specific situation, including the use of insulating materials such as Kaowool or Fiberfrax wrapping.

Here are the guidelines for gate and feeder bar sizing:

Gate and Feeder Bar Sizing

- From the Riser Design Wizard, calculate the maximum modulus of the feeding zone.
- The 2-D modulus of the casting end of the gate will be equal to the maximum modulus.
- The 2-D modulus of the feeder bar end of the gate will be 1.2 times the maximum modulus.
- The 2-D modulus of the feeder bar will ALSO be 1.2 times the maximum modulus.
- For a square cross-section, the modulus is the edge length/4.

So, once we know the maximum modulus in the casting, or the feeding zone, we can calculate the appropriate size for a tapered gate, as well as feeder bar dimensions that will adequately feed that part of the casting. This calculation is done in the Riser Design Wizard, which was originally designed to calculate cylindrical risers for the sand casting process. However, it provides good information for investment castings, too. An example of the wizard screen is shown here:

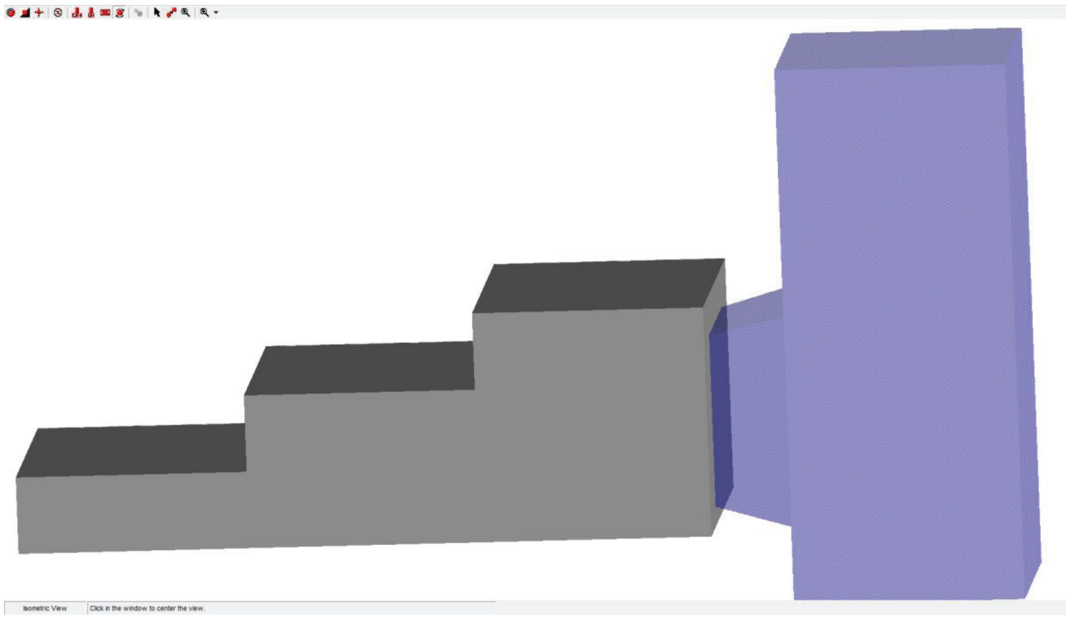


Modulus calculations are used to size both the tapered gate and the feeder bar.

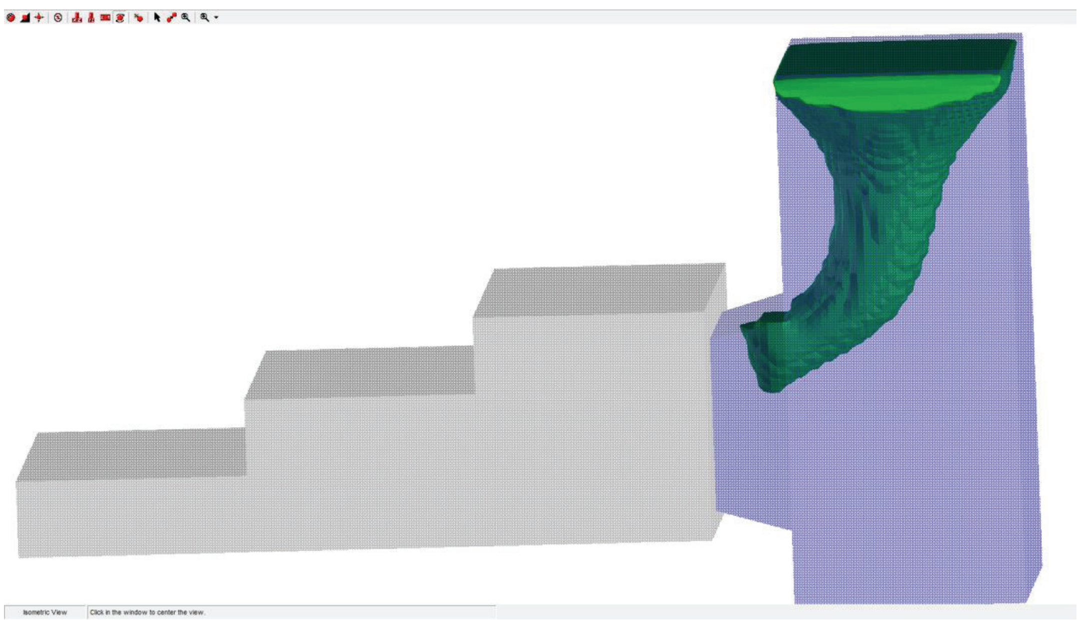
Modeling the Rigging System

Gate and feeder bar calculations, as outlined above, will normally take only a few minutes to perform. Rigging components can be created in CAD or in the simulation software itself. Items that will be used for more than one casting, such as a standard size of pouring cup, can be created in a component format, and re-used as needed, thereby saving considerable time in the model creation phase.

If a library of gating components is developed and used, the entire rigging design process, from loading the unrigged model to having a fully rigged geometry ready for verification simulation, can be as short as 30 minutes or so.



Tapered gate and feeder bar added to the casting model.



Simulation of rigged model, showing feeding from the bar is adequate for a shrink-free casting.

Design Verification Using CFD and Solidification Analysis

Once the rigging system is in place, a full Computational Fluid Dynamics (CFD) analysis is performed to accurately predict and visualize mold filling. This also provides the most accurate temperature distribution in the casting and mold, which, in turn, provides a better solidification analysis.

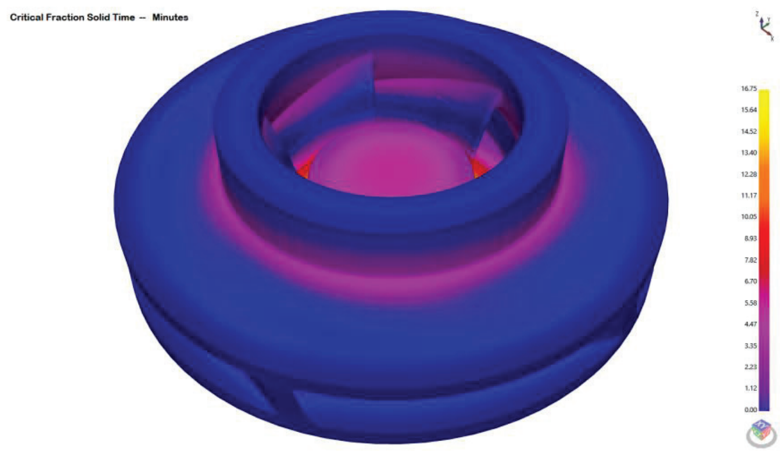
In addition to temperature analysis, CFD can provide velocity information. It is important to keep metal stream velocities low during filling, to minimize chances for splashing and re-oxidation defects.

Filling analysis is automatically followed up with solidification analysis, using a combined thermal and volumetric calculation. This technique not only predicts poor directional solidification, but provides the most accurate analysis of macro-shrinkage due to lack of volumetric feeding from the rigging system.

In many cases, the design portion of the analysis can be done in an hour or less. Verification simulations, using full CFD analysis, can be done typically in about two hours to overnight. Simulation times will vary depending on such things as computer processor speed and available memory, casting complexity and materials cast. In general, thinner walled castings require more computation time, and materials with higher thermal conductivities, such as aluminum and copper, will also take longer to simulate, all things being equal.

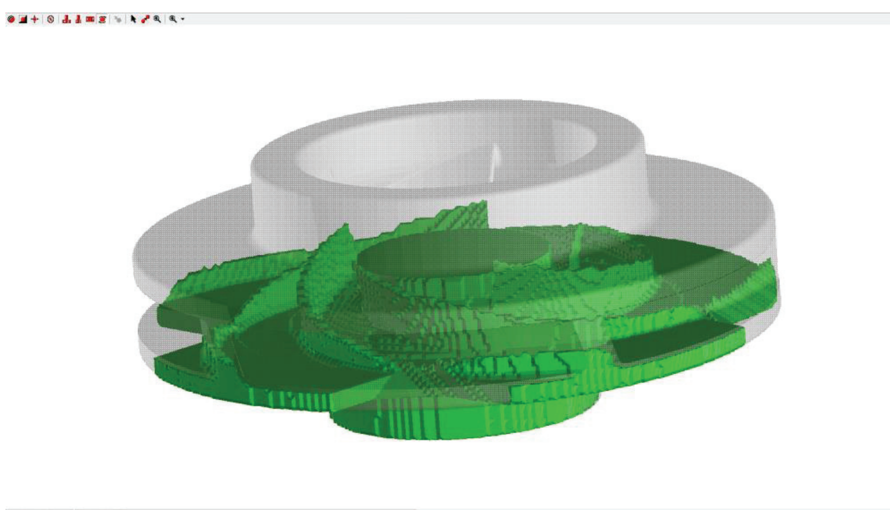
Case Study – Impeller Casting

Our example of a commercial part is an impeller casting. Shown below are the results of the unrigged simulation:

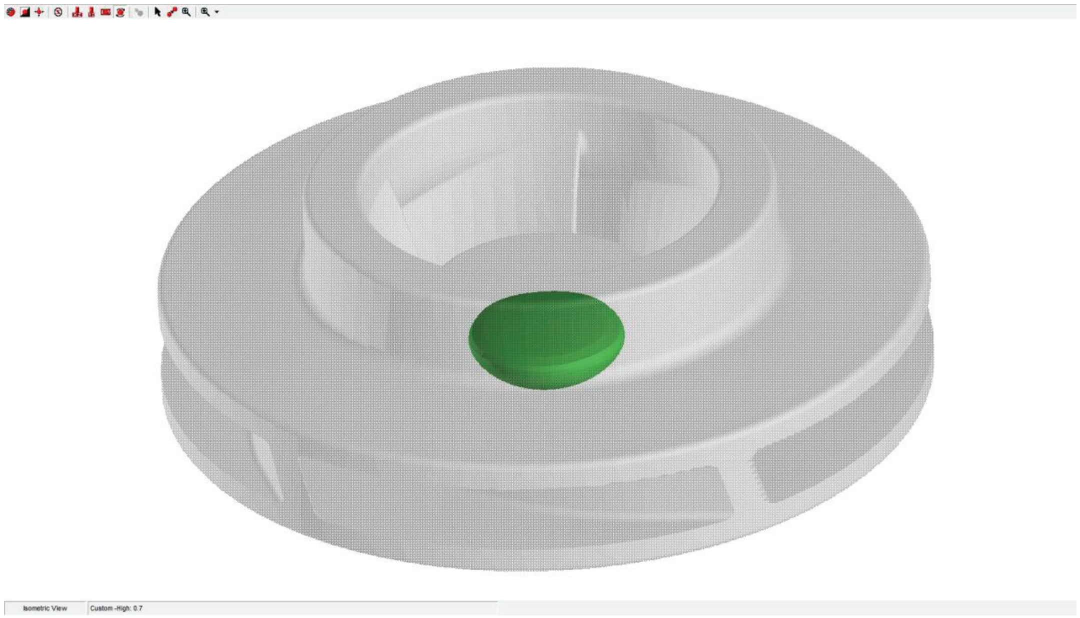


STL model of an impeller casting. 'Naked' simulation results, without filling.

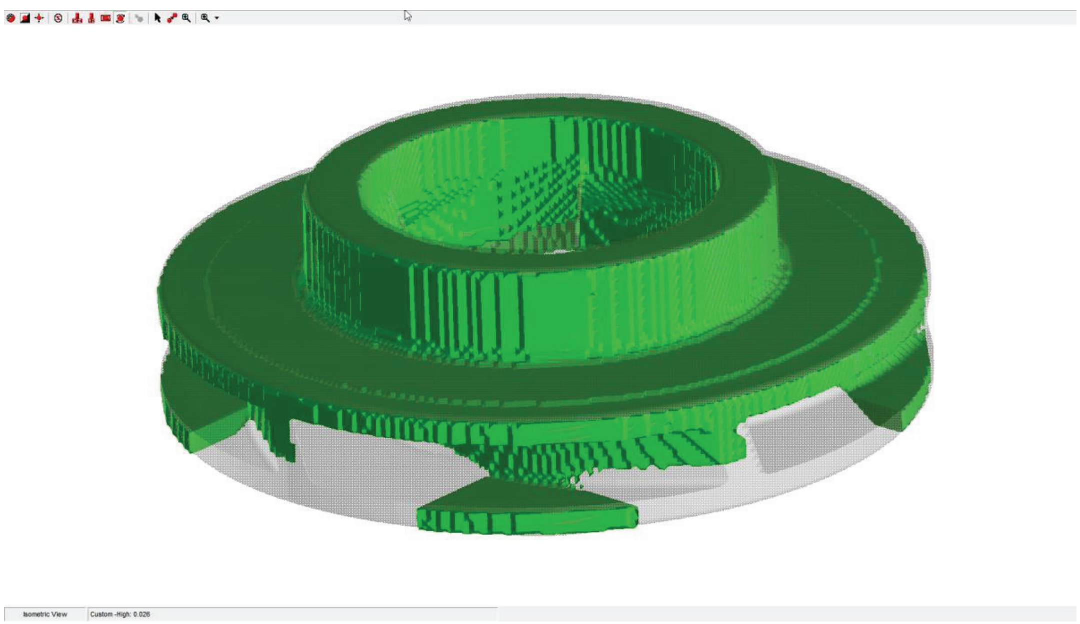
Once the unrigged simulation was complete, the data was converted to thermal modulus information, and the feeding zones were predicted. In this case, two separate feeding zones are predicted; one on the top and one on the bottom of the casting. By plotting the higher modulus areas, we can find the preferred gate attachment points. The feeding zones and last points to freeze on each zone are shown following:



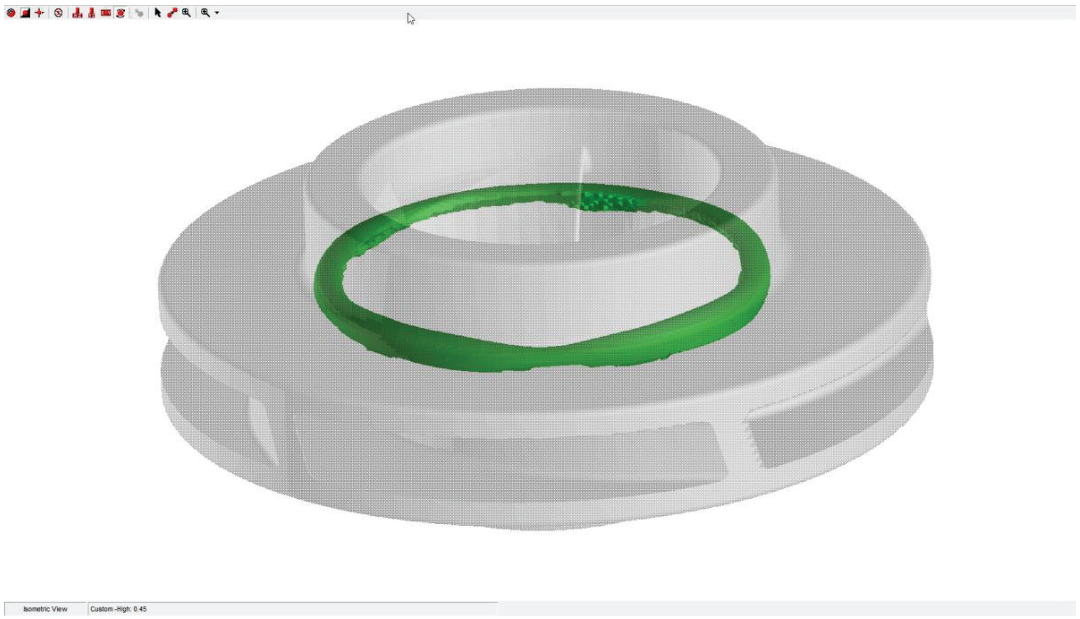
Feeding Zone #1



Last Point to Freeze on the Zone

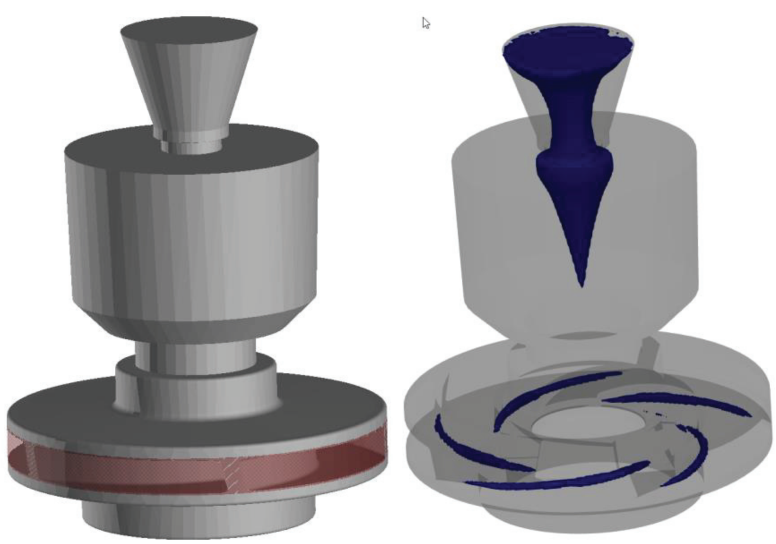


Feeding Zone #2



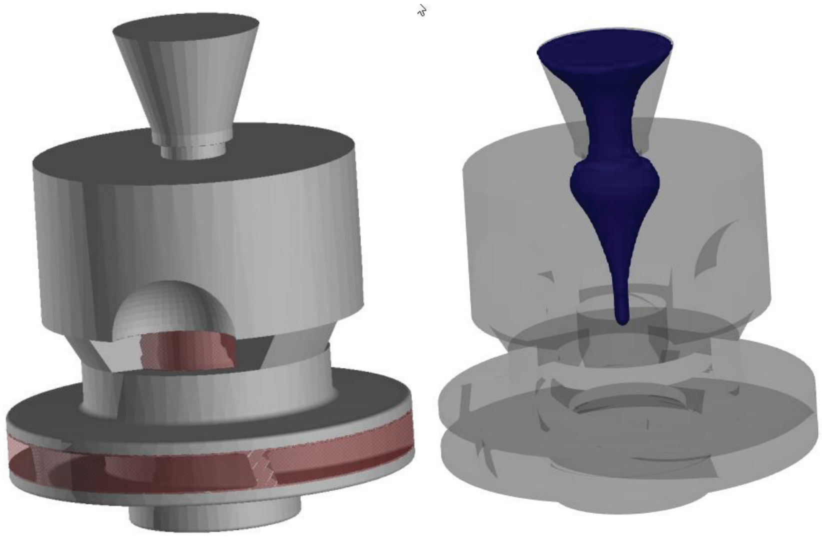
Last Point to Freeze on the Zone

One of the things that feeding zone analysis does NOT tell us is the effect of metal flow. In this example, the foundry decided to invert the casting and gate on the top of the solid boss, hoping that the filling process would create temperature gradients for directional solidification. Here is what the initial design looked like:



Initial rigging design and Material Density plot, showing areas of poor feeding.

Unfortunately, filling did not have the desired effect, and there were isolated areas in each vane, as shown in the plot on the previous page. The foundry then flipped the casting over, and provided multiple gates into the top flange. The revised model and results are shown here:



Improved feeding results by inverting the casting and adding multiple gates on the top flange.

This example shows clearly why it is important to verify the rigging design with a full simulation, including fluid flow analysis. It is impossible for 'rules of thumb' to take into account all the variables and dynamics of a process as complicated as the filling and solidification of castings. However, those rules can help us get to a good rigging design much more quickly than by simple trial and error.

Conclusion

Casting simulation software has gradually evolved from a problem detection or verification tool to an integrated part of the design method process. Simulation is no longer used simply to check a rigging system, but to actually be the driving force for the design of the system itself. Even complex geometries can be successfully rigged in a short period of time using such tools.

The use of actual simulation results directly in the rigging process produces a more accurate result than manual techniques, and does it in a much shorter time period. This integrated approach reduces overall costs and reduces lead times. A case study was presented to provide a detailed example of how such a tool is applied to commercial castings.