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Pittsburgh, Pennsylvania

70th ANNUAL TECHNICAL CONFERENCE and EXHIBITION

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The Investment Casting Institute would like to thank the following Member companies for their educational support and promotion of the industry.

ARISTO CAST
INVESTMENT CASTING

Larry Blum of Aristo-Cast

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.

70th ANNUAL TECHNICAL CONFERENCE & EXHIBITION

Bridging Investment Casting Technology to the Future

Receptions
Sun. 5:30 p.m.
Tues. 6:00 p.m.
Exposition
Mon. 2:30 p.m. - 6:00 p.m.
Tues. 2:30 p.m. - 5:00 p.m.

SUNDAY, AUGUST 13, 2023

3:00 p.m. - 7:30 p.m.	**REGISTRATION**	
5:30 p.m. - 7:30 p.m.	**WELCOME RECEPTION & AWARD CEREMONY** (Intern Scholarships, Innovator of The Year, Hall of Honor, Member Emeritus)	

MONDAY, AUGUST 14, 2023

7:00 a.m. – 5:30 p.m.	REGISTRATION DESK	
8:00 a.m. – 8:30 a.m.	**WELCOME - GENERAL SESSION** *Nip Singh, S&A Consulting Group, LLP, ICI Director*	
8:30 a.m. – 9:30 a.m.	Keynote Address: Overcoming Organizational Adversity Colonel Greg Gadson*, US Army*	
9:30 a.m. – 10:00 a.m.	**BREAK**	
10:00 a.m. – 10:30 a.m.	How Automation Can Be Used As An Employee Development Platform In The New 'Difficult-To-Hire and Retain' World *Aaron Phipps, MPI, Inc.*	**Booth #413**
10:30 a.m. – 11:30 a.m.	A Research and Industry Roadmap: Barriers and Opportunities for Increased, Lower Cost Additive Manufacturing Integration for Investment Casting Foundries *Christopher Annear, Penn State Behrend*	
11:30 a.m. – 12:15 p.m.	How Is My Pattern Coating and Draining? *Gavin Dooley, REMET UK*	**Booth #101**
12:15 p.m. – 1:00 p.m.	**LUNCH**	
1:00 p.m. – 1:30 p.m.	Training and Recruiting High-Quality Next Generation through Industry Partnered Competitions *Victor Okhuysen, Ph.D., Cal Poly Pomona University*	
1:30 p.m. – 2:30 p.m.	Water Shell Removal Compared to Other Methods *Darrell Terpenning, NLB Corp.*	**Booth #216**
2:30 p.m. – 6:00 p.m.	**EXPO**	

TUESDAY, AUGUST 15, 2023

7:00 a.m. – 5:00 p.m.	REGISTRATION DESK
8:00 a.m. – 8:15 a.m.	**WELCOME - GENERAL SESSION** *John Marcin, Raytheon Technologies Corp., ICI Director*
8:15 a.m. – 9:00 a.m.	Industry 4.0 and the Foundry of Tomorrow *Imed Bourega, Shell-O-Matic* **Booth #213**
9:00 a.m. – 9:30 a.m.	Intercoat Drying and Shell Characteristics for Investment Casting Industry *N. Vigneswaran, SAN Precision Alloys Private Limited*
9:30 a.m. – 10:30 a.m.	Foundry 4.0 – Shell Room Experience with SlurryTrack Inline Viscosity Monitoring and Control System *Dr. Sunil Kumar, Dr. Joe Goodbread, Rheonics GmbH* **Booth #506**
10:30 a.m. – 10:45 a.m.	**BREAK**
10:45 a.m. – 11:30 a.m.	Improved Process and Material Properties in Air Casting Applications by Means of Vacuum CAP (VAP) Furnace Process *Iñaki Vicario, Consarc Engineering Ltd.* **Booth #316**
11:30 a.m. – 12:15 p.m.	The Cyclops Ladle *Jorge Arellano, POK*
12:15 p.m. - 1:00 p.m.	**LUNCH**
1:00 p.m. – 1:45 p.m.	Novel Regular Ceramic Filter for The Lost Wax Applications *Ladislav Tomek, LANIK s.r.o.* **Booth #301**
1:45 p.m. – 2:30 p.m.	Effect of Depressurization on Dimensional Expansion of Turbine Blades Casting Process *Lütfi Yakut, Tubitak Marmara Research Center*
2:30 p.m. – 5:00 p.m.	**EXPO**
6:00 p.m. – 8:00 p.m.	**RECEPTION**

WEDNESDAY, AUGUST 16, 2023

7:00 a.m. – 12:00 p.m. REGISTRATION DESK

8:00 a.m. – 8:15 a.m. **WELCOME - GENERAL SESSION**
Ty Ueland, SeaCast, Inc., ICI Director

8:15 a.m. – 9:00 a.m. Advanced Electrode Melting for Highest-Purity Cast Parts
Dr. Samuel Bogner, ALD Vacuum Technologies GmbH **Booth #113**

9:00 a.m. – 9:30 a.m. An Approach Utilizing Technology to Restore the Metal Casting Industry to a New Level of Pre-eminence
Donald Deptowicz, Aspen Hybrid Technology Solutions LLC
ICI AM Subcommittee Chair

9:30 a.m. – 10:15 a.m. Nadcap Casting Program
Dr. Richard Freeman, PRI

10:15 a.m. – 10:30 a.m. **BREAK**

10:30 a.m. – 11:00 a.m. ICI Process Control Standards and Nadcap Casting Program
Complementary Systems with Different Objectives
Brian Ferg, Member Emeritus

11:00 a.m. – 11:30 a.m. **CASTING CONTEST AWARDS**

11:30 a.m. – 11:45 a.m. **ADJOURNMENT**
Joseph Fritz, ICI Executive Director

SPEAKERS

Col. Greg Gadson **Keynote Speaker**
US Army
Premiere Speakers Bureau
109 International Drive, Suite 300
Franklin, TN 37067
Phone: (615) 261-4000

Aaron Phipps **Paper No: 1**
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Christopher Annear **Paper No: 2**
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Pennsylvania State University
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Erie, PA 16510
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Gavin Dooley **Paper No: 3**
Group Technical Director
REMET UK
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Victor Okhuysen, Ph.D **Paper No: 4**
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Dr. Sunil Kumar **Paper No: 8**
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Dr. Joe Goodbread **Paper No: 8**
Founding Member
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Iñaki Vicario **Paper No: 9**
Casting Technology Specialist
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Jorge Arellano **Paper No: 10**
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SPEAKERS

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Donald Deptowicz **Paper No: 14**
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Dr. Richard Freeman **Paper No: 15**
Principal Staff Engineer
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1 York Street
London, England W1U 6PA
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Brian Ferg **Paper No: 16**
ICI Member Emeritus
6707 Bramblewood Lane
Mayfield, OH 44143
Phone: (440) 461-0255

SPEAKER BIOGRAPHIES

Colonel Greg Gadson ....Keynote Speaker
US Army
Colonel Gregory D. Gadson, a Chesapeake, Va., native, served our nation in the United States Army for more than 26 years. Col. Gadson's service culminated as the Garrison Commander of Fort Belvoir, where he oversaw the daily operations of the post, a strategic sustaining base where more than 50,000 military personnel and employees provide logistical, intelligence, medical and administrative support, and command and control for a mix of more than 140 commands and agencies for the Department of Defense. Col. Gadson's life is a portrait of courage in the face of great adversity. In May 2007, as commander of the 2nd Battalion, 32nd Field Artillery, Col. Gadson's greatest challenge came in Iraq, where an Improvised Explosive Device (IED) attack cost him both legs above the knees and normal use of his right arm and hand. Despite this, Gadson remained on active duty in the Army and continued to inspire many with his message of courage, perseverance, determination and teamwork. Colonel Gregory D. Gadson, a Chesapeake, Va., native, served our nation in the United States Army for more than 26 years.
Col. Gadson's service culminated as the Garrison Commander of Fort Belvoir, where he oversaw the daily operations of the post, a strategic sustaining base where more than 50,000 military personnel and employees provide logistical, intelligence, medical and administrative support, and command and control for a mix of more than 140 commands and agencies for the Department of Defense. Col. Gadson's life is a portrait of courage in the face of great adversity. In May 2007, as commander of the 2nd Battalion, 32nd Field Artillery, Col. Gadson's greatest challenge came in Iraq, where an Improvised Explosive Device (IED) attack cost him both legs above the knees and normal use of his right arm and hand. Despite this, Gadson remained on active duty in the Army and continued to inspire many with his message of courage, perseverance, determination and teamwork. Greg continues a very energetic and dynamic lifestyle where he continues to serve his nation as an entrepreneur and managing partner of Patriot Strategies, LLC, a government services company. He is also an accomplished photographer/artist and remains active in cycling, skiing and scuba. Greg's military awards include the Distinguished Service Medal; Legion of Merit (2); Bronze Stars (3); Purple Heart; the Meritorious Service Medal (3) and the Army Commendation Medal (3). He is a graduate of Command and General Staff College at Fort Leavenworth, Kansas; and holds masters degrees in Information Systems from Webster University; and Policy Management from Georgetown University. He holds an honorary Doctorate of Laws from Webster University.

Aaron Phipps...Paper No: 1
President – MPI, Inc.
Aaron Phipps is the President of MPI, Inc. Aaron is the son of founder Bruce Phipps and has been with the company in an official capacity since 2010. In truth, Aaron has been in and around the investment casting industry his entire life. Aaron has an engineering degree from Rochester Institute of Technology. He currently teaches the wax section of the Certification Course for the Investment Casting Institute. He presented a paper at the 2015 ICI Technical Conference entitled, “Current Problems in the Wax Room and How they are Best Overcome,” and also presented at the EICF World Conference in Paris a paper entitled, “Overcoming Common Wax Injection Problems: The First Step toward Automation.” He sits on the Advisory Board of the New Paltz School of Science and Engineering, receiving an award for invaluable contributions to the school’s Internship Program. Prior to joining MPI in an official capacity, Aaron worked at A.W. Bell in Australia as a product engineer and in the Bio Medical industry. After joining MPI, Aaron worked his way through MPI taking on key roles including product and automation engineering, process engineering, establishing a training curriculum, department manager, VP of Sales and Service, VP of Manufacturing and Engineering and now President. After working in all phases of engineering, Aaron took over the MPI Technology Center as manager, overseeing critical areas of the business including pattern production services, demonstrations, process validation, testing and operator/engineer training. The Technology Center is MPI’s state-of-the-art facility where engineering, innovation and R&D intersect to create real-world solutions to customer’s wax room challenges without having to interrupt their production. MPI has experienced explosive growth in recent years, having doubled in size. Aaron has been an instrumental contributor to this growth as a talented problem solver who effectively collaborates with customers and vendors alike to develop solutions for a wide array of challenges.

Christopher Annear ....Paper No: 2
Undergraduate Student – Pennsylvania State University
Christopher Annear is a Schreyer Honors College undergraduate student at Penn State Erie, The Behrend College. Chris is majoring in Industrial Engineering with a minor in Operations & Supply Chain Management.

SPEAKER BIOGRAPHIES

Gavin Dooley .... Paper No: 3
Group Technical Director – REMET UK
Gavin studied Mechanical and Manufacturing Engineering in Trinity College Dublin, Ireland and a PhD from the University of Birmingham, UK. Gavin's PhD was entitled "Shell Improvements for the Investment Casting of Orthopaedic Implants". He has been in the investment casting industry for over 11 years in various roles including, research, process and materials engineer and technical director. He also holds an MBA from the Open University. Gavin supports Worldwide product development, customer technical service and quality for the REMET Group. Gavin has presented numerous presentations in Europe, US and Asia in recent years.

Victor Okhuysen, Ph.D. .... Paper No: 4
Professor – Cal Poly Pomona
Dr. Okhuysen has held jobs in academia and industry. He has been a Professor of Industrial and Manufacturing Engineering at Cal Poly Pomona since 1998. Prior to his academic career he held various positions in the Metal Casting industry the last of which was as Engineering Manager at CMI-Tech Cast Foundry in Myerstown, PA. In his academic career Dr. Okhuysen has taught multiple courses in areas related to Manufacturing, Materials and Industrial Engineering. He has had multiple research projects, typically in partnership with industrial entities and some sponsored by government agencies. He has many articles and presentations in the area of Metal Casting. As a Professor he has won several awards including the 2015 Outstanding Academic Advisor from the College of Engineering, the Outstanding Faculty Award from the Veteran's Resource Center and the Distinguished Professor Award from the American Foundry Society and the Foundry Educational Foundation.

Darrell Terpenning…....………………………………………………………………………………….....……Paper No: 5
Vice President of Domestic Sales - NLB Corporation
Darrell Terpenning joined NLB Corporation in 2013 as the Vice President Sales covering the United States and Canada. He received his bachelor's degree in Businesses Administration with an emphasis in Management and Finance, from Cedarville University in 1986. Mr. Terpenning started his career as a contractor at ARAMARK Industrial Services, focused on cleaning Industrial Plants and in Automotive Paint Shops both domestically and internationally. Gaining experience in various cleaning processes and developing new process for both facilities and production components. In 1999, he joined MPW Industrial Services Inc as the Director of Labor and Support Services. At MPW he expanded his experience into new applications. From 2001 through 2012, Mr. Terpenning led the sales and operations for Total Filtration Services, starting as the Director of Automotive then the Director of Branch Development then moving into the Director of National Accounts. At Total Filtration Services, he gained additional experience with production applications. Today Mr. Terpenning, leads the sales team for the United States and Canada for NLB Corp, the leading supplier of high pressure water jetting pumps in industrial cleaning. Focused on new applications and further developing markets using high pressure water to successfully and sustainably clean or process manufactured components.

Imed Bourega…....…………………………………………………………………………………….....….....Paper No: 6
President & CEO – Shell-O-Matic
Imed Bourega is the President & CEO with Shell-O-Matic since May 2021, he holds a master's degree in automation and brings over 25 years of extensive experience in automation. Imed started his career as a system engineer with an Oil & Gas company based in Algeria. He then held different senior positions in Sales, Marketing, Business Development, Strategic Planning and General Management with some of the world's leading automation solutions companies, including Honeywell, Emerson, and Schneider Electric. Imed has worked in Europe, Middle East, Africa and in Canada. Before joining Shell-O-Matic, Imed was working with the exclusive representative of Emerson Automation Solutions in Eastern Canada as Vice President for Systems, Solutions and Digital transformation. In this role, he helped customers thrive by co-developing with them their digital transformation strategy to reach and sustain top quartile performers.

SPEAKER BIOGRAPHIES

N. Vigneswaran……………………………………………………………………………………...………………..…Paper No: 7
Director – SAN Precision Alloys Private Limited
Mr. Vigneswaran Nagarajan has a Master Degree in Industrial Metallurgy and a Bachelor Degree in Mechanical Engineering, basically from a metallurgical family while his father Mr.Nagarajan.R , is well known technocrat in heat treatment of Metals in South India. Since his graduation he is looking after and supporting his father as Director of the following group of companies:
1. M/s. BEST Heat Treatment Services, Tamilnadu, India.
2. M/s. BEST Induction Services, Tamilnadu, India
3. M/s. BEST Valve Components.
4.M/s. Vignesh Metal Process

He has implemented various techniques in the process of Heat treatment like development of Jigs & Fixtures to improve productivity, optimization of heat treatment cycles, maintaining a good reputation with the customers by providing excellent service in the area of Quality, Delivery and Cost. Under his leadership, various reputed companies both public and private limited has awarded the best supplier in the field of Heat Treatment. With this his thirst for engineering is not satisfied, hence started an manufacturing unit of Investment Casting as M/s. SAN Precision Alloys Private Limited. With the past experience and his reputation in the field, hard work, dedication, he has elevated the company to an annual turnover of 5 Million USD and proved as one of the best supplier in the field of automobile, aerospace, valves, medical devices, serving both domestic and international customers. He has been awarded the following during these period of service and still working hard in the field of Marketing, establishing Innovative techniques in the process of investment casting, optimization of process to improve productivity, reducing cost and rejections.
1. PSG Alumni Award in the Year 2016
2. CEO of the year 2020 by CEO History Magazine

Dr. Sunil Kumar .... Paper No: 8
CEO - Rheonics GmbH
Sunil is founder and CEO of Rheonics. He has extensive experience in the industrial automation, having worked in a variety of roles in engineering and research in his early career. Most recently Sunil worked at Baker Hughes where he led global engineering for drilling Services. Sunil founded companies in US and UK that successfully commercialized innovative products. He graduated with Bachelors in Aerospace from Indian Institute of Technology, Kharagpur, Masters in Mechanical engineering from University of California, Irvine and Ph.D in Electrical engineering from Imperial College, London where he developed the Seis-SP seismometer that is part of the main payload for the NASA Insight mission to Mars. He is a prolific inventor with over 40 patents and multiple peer reviewed papers.

Dr. Joe Goodbread .... Paper No: 8
Founder – Rheonics GmbH
Joe is a founding member of the team that developed Rheonics' core technologies over the past 30 years. He established and directed the Experimental Mechanics Laboratory at the Institute for Mechanics, ETH Zurich. He has developed substantial IP in the field of fluid properties sensors with 18 granted patents and several more pending. He has a BSE in Aerospace and Mechanical Engineering Science from Princeton University, a MS in Biomechanics from Stanford University, and a Dr. Techn. Sc. from the ETH Zurich in Biomechanics. Early in his career, Joe worked with SRI (Stanford Research Institute, then) and thereafter headed the IMES labs at ETH Zurich. Joe is also a trained psychotherapist and a founder of the Institute of Process Work. He is an author of 4 books on the subject. Joe's extensive research and engineering skills form the technical core of the rheonics' products and services. His passion for innovation and tackling impossible challenges has created industry leading products.

Iñaki Vicario…….…….…………………………………………………………………………………….……….Paper No: 9
Casting Technology Specialist - Consarc Engineering Ltd
Iñaki Vicario is the Casting Technology Specialist of Consarc Engineering. He belongs to the Technology Group of Consarc dealing with technical developments, and customer technical support. He has almost 15 years of experience in the aerospace industry, specifically in investment casting technology as a foundry process owner, and also, as casting process specialist in several worldwide and high demanding vacuum casting projects. He has also large experience in other metallurgical processes, such as vacuum heat treatment (10 years of experience in AMS 2750), VIM process for Ni based alloy manufacturing, HIP and gas phase aluminizing. Mr. Vicario has a Bachelor's degree from the University of the Basque Country in Industrial Engineering, specialized in Manufacturing Technologies.

SPEAKER BIOGRAPHIES

Jorge Arellano……....…………………………………………………………………………………..……….Paper No: 10
R&D Process Engineer - POK
Jorge Arellano studied Materials Science Engineering with a minor in Metallurgy and had the opportunity of being FEF student for almost 3 years representing Instituto Tecnológico de Saltillo in several projects. He also has a Bachelor in Business Administration and is currently studying an MBA in Financial Management. Jorge has been working for almost 2 years at POK Castings (A Nucor Company) in several positions involving Quality Engineering and R&D Process Engineering (current). In 2022, he had the opportunity of being part of the 20th ICI Certification Program, and since then, he has been participating as a technical support, research, and continuous improvement in investment casting industry.

Ladislav Tomek..………………………………………………………………………………….……….....Paper No: 11
Sales Engineer – LANIK s.r.o.
Ladislav Tomek graduated from the Brno University of Technology (BUT), Institute of Manufacturing Technology, department of Foundry Engineering in 2008. His master thesis was focused on the interaction between iron castings and cement sand moulds. He joined LANIK s.r.o. company in 2008 as sales engineer and since 2011 his specialization is the lost wax process with focus on applications of ceramic foam filters, ceramic cups and cores. Since 2019 he has been involved in collaboration with Brno University of Technology (BUT) and development of investment casting technology at the BUT workplace. Member of the Czech Foundryman Society.

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***Project Manager -* Tubitak Marmara Research Center**
Lütfi is from İstanbul / Turkey. He graduated from Marmara University faculty of Metallurgy and Materials Science Engineering in 2017 B.S. The same year he went to Politechnica Lubelska / Metallurgy and Materials Science Engineering for student exchange. Next year he joined Marmara University Master Degree / Metallurgy and Materials Science Engineering he started working on Powder Metallurgy for thesis and finished M.S in 2020. During M.S, he started working at a industrial furnace manufacturer as production development engineer till 2019. Since 2019 he is working at TÜBİTAK Marmara Research Center, working on single crystal and directional solidified turbine blade castings, investment casting, Tripple melting(VIM/ESR/VAR) of superalloys development and leading as project manager since 2021. In 2022 he joined his Ph.D. at Marmara University Ph.D. / Metallurgy and Materials Science Engineering.

Dr. Samuel Bogner……...………………………………………………………………………………………...Paper No: 13
Product Manager – ALD Vacuum Technologies GmbH
Samuel Bogner studied material science at University of Stuttgart in Germany and finished his diploma thesis "Solid State Electrochemical Characterization of Thermodynamic Stabilities of Sodium Titanates" in 2008. Samuel Bogner worked as a research assistant in the field of directional solidification and investment casting at the Foundry Institute of the RWTH Aachen University. He obtained his doctoral degree "Process development of the manufacturing of in-situ composites by directional solidification of eutectic NiAl alloys" in 2018. His professional career started as an R&D engineer at ALD Vacuum Technologies GmbH in 2016 and he currently works as a product manager in the ALD casting & coating department

Donald Deptowicz .... Paper No: 14
Senior Executive – Aspen Hybrid Technology Solutions LLC
Don Deptowicz is a Results Oriented Senior Executive with an outstanding track record in engineering, program management and quality. He excels at being an inspirational and resourceful leader. He is known for innovative and creative thinking in the areas of both product and process designs involving advanced materials and coatings. He is an exceptionally skilled communicator, with the ability to build effective and productive working relationships across all levels of the organization and the value chain. Don graduated from Purdue University, and began his career in 1976 at UTC's Pratt & Whitney Engine Division in West Palm Beach, Florida. Here, he led fundamental changes in both product and manufacturing process technology, covering the full life cycle of Military Aerospace Propulsion Systems. Don has over 47 years of experience in the aerospace, automotive and electronic industries. Prior to this, he was the Director of Technical Excellence for PCC Airfoils LLC, where he championed the collaborative effort across engine OEMs and casting suppliers in conjunction with the Air Force Man Tech vision of Attaining Next Generation Agile Manufacturing.

SPEAKER BIOGRAPHIES

Dr. Richard Freeman..Paper No: 15
Principal Staff Engineer – Performance Review Institute (PRI)
Richard Freeman worked for Collins Aerospace in the UK from 1990-96 as a Production Metallurgist, dealing with the manufacture of a wide range of actuation components, including investment castings. He then joined TWI, a UK R&D technology consultancy, in 1996 where he led the aerospace industry sector activities, eventually becoming an Associate Director in the company. After 25 years at TWI he joined the Performance Review Institute (PRI) in late 2021, to lead the Metallic Materials Manufacturing Task Group as a Principal Staff Engineer. PRI administers the Nadcap program, and the Metallic Materials Manufacturing Task Group covers the manufacture of forgings, sand and investment castings, on behalf of the aerospace OEM community. Richard obtained a BSc Honors degree in Metallurgy in 1987 from Sheffield University, and a PhD in 1994 while working full-time on some R&D projects at Collins Aerospace. He is a UK Chartered Engineer and a Fellow of the Institute of Materials. He has been the UK representative on the ISO TC44 SC14 welding in aerospace committee, and also the ISO TC 261 committee with ASTM F42 on additive manufacturing for aerospace for the last 14 years. He also represents the UK on the AWS D17 welding in aerospace committee, and has done for 25 years. Richard will be speaking at this event on the Nadcap casting program.

Brian Ferg………...….....Paper No: 16
Retired – ICI Member Emeritus
Brian Ferg is a retired engineer having worked in the investment casting industry for over 45 years. His career path included time with Sherwood Refractories, TRW, PCC, ESCO, and CPP. With a ceramic engineering degree from Penn State and GE certified Black Belt, Brian specialized in the development and process control of a wide range of areas including ceramic cores, wax assembly, shell systems, and casting operations for both air melt and vacuum melt castings.

INVESTMENT CASTING INSTITUTE

How Automation Can Be Used As An Employee Development Platform in The New 'Difficult-to-Hire and Retain' World

Aaron Phipps
MPI, Inc.

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 1

Title: How Automation can be used as an employee development platform and cost-saving tool in the new "difficult-to-hire-and-retain" world.

Introduction:

The current business landscape is highly competitive, and organizations are struggling to hire and retain employees with the right skills and attitude.

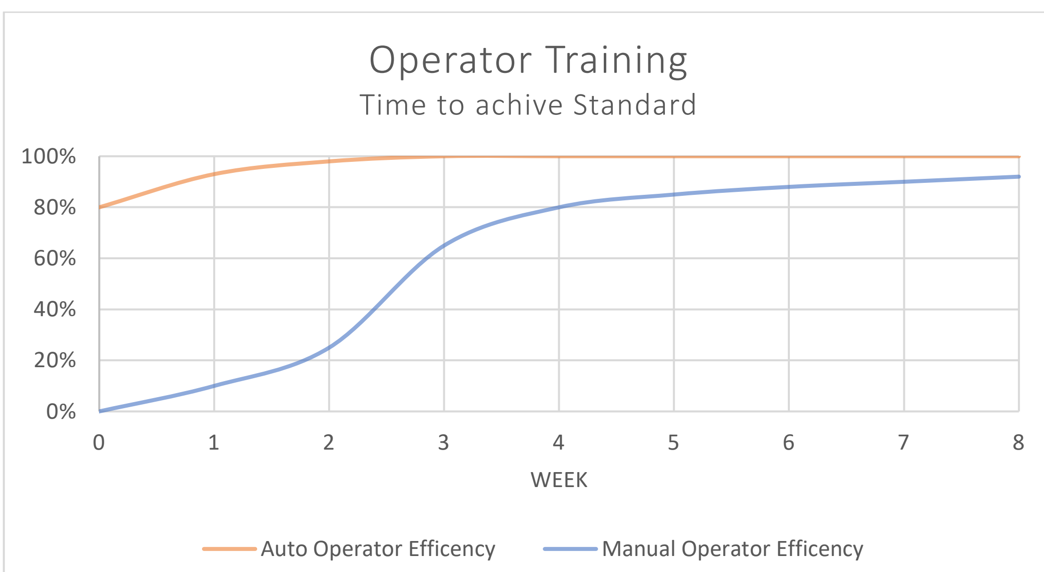
At MPI, we have experienced similar challenges finding talented individuals who have the aptitude to learn the skills required for our wax room pattern injection and pattern assembly business.

Historically, the wax room has been considered a low-pay training-intensive department, making it challenging to retain employees who are satisfied doing these tasks as a career. Training to make manual assemblies used to take 3-6 months to produce high quality, repeatable assemblies. Along the way there were high scrap rates and lost opportunities. Through automation, however, we were able to transform this department into a lower-skill entry-level high-value-added position, attracting employees who are enticed by working with technology.

Benefits of Automation as an Employee Development Platform:

I. Increased engagement and evaluation
II. Reduction in Cost and Time
III. Creation of a Career Growth Path
IV. Increased Standards for Hiring

1. Increased engagement and evaluation: We have observed our entry level employees are able to add value on day one, which increases their engagement from the outset. We can train them and develop them on company culture and values while evaluating them for aptitude and attitude, providing a clear growth path for them to develop a career at our company. Automation allows us to build up an employee's confidence and bring out a higher potential than was evident previously through higher engagement and morale.



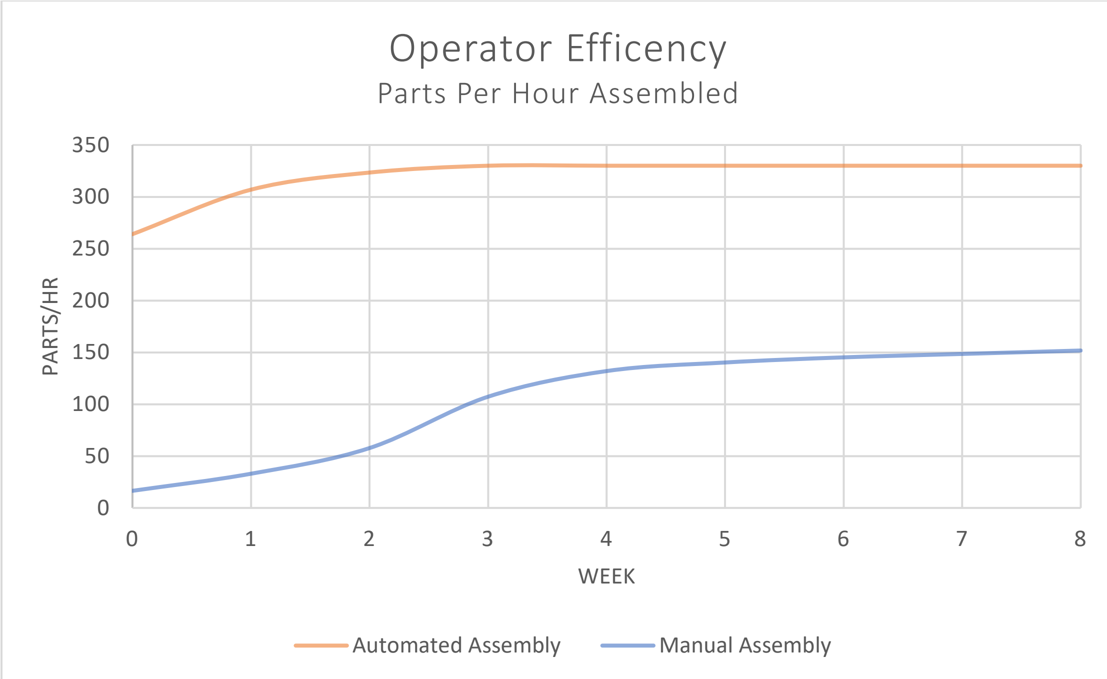
Manual Progression towards productivity:

i. Week 1: will be start of production work. Everything will need to be checked over. They will be working slowly and methodically to ensure quality. Assemblies will take 3-5x longer than the standard.
ii. Week 2-3: is the inflection point. This is where it will be apparent whether and operator has the ability to consistently weld patterns. At this point 80 to 120hr.'s have been invested in training the operator. If they are capable of welding, they should be getting faster and assembly times will be ~60-70% of the standard. Work should still be verified by another operator.
iii. Week 4: an operator should be able to assemble without another operator verifying their work. They should be able to make defect free assemblies at about 85% of the standard time.
iv. Week 4+: The operator will be getting faster at assembly, working closer towards standard times. It may take another 4-6 weeks for the operator to assemble at ~100% of the standard time. Some operators may never be able to hit the standard.

Automated Progression towards productivity:

i. Week 1: The operator should be able to run quality assemblies on the machine in under an hour of training. Their training will continue as they run quality product. They know how to startup and operate the machine to run existing recipes.
ii. Week 2: It should be apparent by this point whether the operator is a good fit for the type of work they will be doing. They will continue to have questions but should be running the machine at or near the standard operator time.
iii. Week 3: The operator should have a solid understanding of the process and what goes into making a quality assembly. They should be capable of pattern and assembly quality inspection.

- By moving to automation MPI has recognized a ~200% potential increase over a fully trained operator
- At MPI we are able to capitalize on an increase in capacity of over ~500% in the first 3 weeks of operator training
    - This allows us to engage with our team in more creative ways and focus on personal development.
- MPI's intuitive operator interface has become the primary training aid, drastically reducing the effort and cost of job set up and change over.



2. Reduction in Cost and Time: Automation has reduced the time and cost to evaluate a new employee for aptitude, attitude and fit in with our company culture. Our onboarding process now starts in the wax room, where a new employee is making perfect wax assemblies and outperforming the most talented manual assembly people.
   a. Furthermore, we've seen an immediate reduction in scrap rates, increased profit margins and decreased lead time.
      i. Operator efficiency parts/hr. is based on 3/min (man) and 6/min (auto) over 55 minutes/hour. This is to account for assembly change over. For manual assembly this is most likely much better than any operator will achieve.
   b. Lower cost results in higher profit margins when comparing work produced via automation versus manual.

Assembly	Pat Per Assembly	Weld Per Min	Assembly Time (min)	Assembly Per hr.	Cost	Savings/Assembly	Savings/Part
A Man	15	3	6	10.00	$5.93		
A Auto	15	6	3.5	17.14	$3.57	$2.36	$0.16
B Man	30	3	11	5.45	$10.35		
B Auto	30	6	6	10.00	$5.68	$4.67	$0.16
C Man	60	3	21	2.86	$19.16		
C Auto	60	6	11	5.45	$9.89	$9.27	$0.15
D Man	120	3	41	1.46	$36.92		
D Auto	120	6	21	2.86	$18.27	$18.65	$0.16

- An increase of nearly 2X throughput
- A decrease of nearly 50% of cost
- A significant increase in profitability
- *Increased ability to win new orders and bid more competitively.

Estimates were made using the following assumptions:

- Manual Assembly 3 Weld/Min
- Auto Assembly 6 Weld/Min
- 1 Min/Assembly changeover time for both
- 5% Scrap on manual Assembly

3. Creation of a Career Growth Path: Automation has enabled us to provide a growth path that previously did not exist, allowing our employees to be productive and trained for other value-added processes within the wax department and other departments within the company. Year to Date, we have hired four new employees to work on the automation equipment in our wax room. Two of them have already transitioned into entry-level machine technicians.
4. Increased Standards for Hiring: Because of automation, we have increased our standards for who we will hire, replacing warm bodies with driven talent. This approach has enabled us to attract employees who are enticed by technology but do not have the background or job history that allows them a hands-on technical career.

Benefits of Automation in the Wax Room:

We have as a part of our business a Technology Center where we support our customers with pattern injection, pattern assembly, and process development. We specialize in duplicating our customers' processes with their materials and their work instructions. We then collaborate with them to automate these processes.

Most of the customers we work with are job shops who have low volume short run production. We saw an opportunity to take our knowledge of automation and develop an assembly solution with a 5-assembly break even when compared to manual assembly.

We worked with several customers using their real parts and production requirements and realized the following benefits:

1. Dramatically reduced one-time tooling costs from over $15,000 to under $500 when compared to traditional automated pattern assembly. This is a 98% reduction!
2. Less than one hour to set up and begin production of a brand-new part number.
3. The process lives in the machine, not in the operator, or the process engineer.
4. On-the-fly adjustments to the standards, such as adjusting spacing, number of parts on a runner bar, and orientation with no robot programming.
5. User friendly controls for set up and operation with no robot training necessary.
6. Training a new operator to run the new job in about 10 minutes.
7. In about two hours, a new operator can be taught how to set up a new job recipe.

Conclusion: Automation can have a positive impact as an employee development platform in the new "difficult-to-hire-and-retain" world we now live in. Through automation, the employee onboarding process can be transformed, reducing recruiting dollars and efforts, training dollars and hours, retention dollars and efforts all while increasing profits, customer satisfaction, competitiveness and reducing lost business opportunities.

INVESTMENT CASTING INSTITUTE

A Research & Industry Roadmap: Barriers & Opportunities for Increased, Lower Cost Additive Manufacturing Integration for IC Foundries

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70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 2

A Research and Industry Roadmap: Barriers and Opportunities for Increased, Lower Cost Additive Manufacturing Integration for Investment Casting Foundries

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Keywords
Additive Manufacturing, Investment Casting, Cost Analysis, Filaments, Ceramics

Abstract:
Additive manufacturing techniques have revolutionized the investment casting industry over the last decade. The fabrication of patterns using an additive technique has proven an effective way to significantly reduce the lead time and cost of low-volume investment castings in a way that can be easily integrated into many existing foundry processes. However, many existing foundries still have not made the capital investment to implement these technologies in-house and are outsourcing the patternmaking to *job shops* that specialize in additive manufacturing. This paper builds off of recently completed and ongoing research with lower cost additive manufacturing systems and design to detail a cost-effective way to begin integrating this technology directly into investment casting foundries while outlining some of the open research topics to be explored for increased and optimal low-cost additive manufacturing integration.

1. Introduction

Investment casting is a widely used manufacturing process which consists of an expendable wax pattern and ceramic mold to create precise ferrous or nonferrous alloy castings. While this process is well known for its ability to create near-net shape castings, it is also associated with expensive tooling costs to create these castings. Due to the complexity of the process and high expenses, traditional investment casting is often limited to small parts with high production volumes. This paper aims to identify modern technologies that can counteract these common disadvantages of investment casting and identify innovative processes for foundries to utilize that allow for investment casting to be cost effective for complex designs and low-production volumes. This paper seeks to hone in on a discussion and explanation of how low cost FDM printing utilizing cost effective PLA filament can increasingly be integrated into investment casting foundries.

As of now, companies are experimenting with fused deposition modeling (FDM) patterns in investment casting [1]. FDM consists of extruding a melted polymer and allowing it to solidify by cooling. Since the FDM pattern replaces the traditional wax pattern, this removes the need for injection molds and the associated tooling [1]. There are also some burdensome changes that must be made to utilize FDM, but the money saved from eliminating the injection mold tooling makes up for these slight alterations. For FDM to be successful, vents must be added to the casting tree, the thickness of the ceramic mold must be increased, and the burnout process must be extended [1]. By making these alterations, wax/plastic patterns can be printed directly with FDM for investment casting.

Additionally, stereolithography (SLA) printing has proven itself to be superior for 3D printing investment castings due to its dimensional accuracy [2]. This process utilizes ultraviolet (UV) light to cure the layers of the resin to form the part [3]. The resin is bonded and hardened in the areas that are exposed to the UV light, and this process is repeated for each layer of the design [3]. The SLA process has been perfected to the point where lenses and windows can be produced, and the dimensions are able to be kept to tight tolerances [3]. For production, this process is being more commonly used to create patterns for investment casting due to being able to print resins that can burnout easily and hold tight dimensional tolerances [3].

Digital Light Processing (DLP) printers have proven to be a cost-effective alternative to SLA printers for investment casting. Similar to SLA printers, DLP printers utilize ultraviolet (UV) light to cure the layers of the resin forming a high-fidelity part. The main difference being DLP printers utilize a screen with pixels amplified by lenses instead of a laser guided by mirrors. Due to operating via a high-resolution digital screen DLP printers have significantly fewer moving parts and require less intensive tuning and maintenance. With recent advancements in screen production pixel density has significantly increased leading to multiple 8K definition printers on the market available for under $600, making these machines available to hobby grade users and facilities with a smaller amount of capital funds.

Lastly, MultiJet printing utilizes the strengths of both SLA and FDM printing through printing parts by layer using a guided deposition system that deposits layers of resin followed by a UV light to immediately cure the resin. With this system multiple resins can be used in the same print allowing for easily removable support materials that can be separated from the part in a solvent bath, allowing for the creation of parts with internal geometries that would be impossible to print with any other method [4]. In addition to the geometries possible with this method of printing, these machines can use a variety of exotic materials ranging from materials such as high temperature polymers that can be used for the creation of temporary injection molds [5] to specialty formulated wax-like polymers designed specifically for investment casting to be burned out in mold making.

This paper is organized as follows: Section 2 provides a summary of the skillsets needed for additive manufacturing in the investment casting industry. Section 3 identifies the relative costs associated with these new 3D printers, and dives into the complexities of the 3D printing options. Sections 4 and 5 discuss the current role that FDM and SLA/DLP printers play in the investment casting industry for wax and polymer printing along with direct printing of ceramics for pattern production, respectively. Section 6 is a rudimentary timeline to demonstrate how 3D printing in an investment casting foundry could be implemented. Section 7 provides a summary of various printing technologies applicable to investment castings along with a technology implementation flowchart for the future of investment casting.

2. Skillsets Needed

For the effective utilization of additive manufacturing, a novel skillset comprised of a deep knowledge of slicer software settings, machine tuning/maintenance, printed material properties, and printer capabilities is needed. When creating a part on a printer the first step is creating the code for the printer. This is accomplished by importing a 3D model into a slicer software to generate the code for the printer to print the part. Outside of creating an effective code for the machine, maintaining, and modifying the printer and its settings is vital for creating quality prints. Another vital skill for creating prints is a knowledge and familiarity with the material used in printing, different materials require different print settings, have different physical properties, and will shrink or warp after printing. Having a thorough understanding of the capabilities of various printers is crucial when determining how a job will be done. Knowing the printer's level of detail, capability to reliably print material, and the operation cost all play a key role in planning.

Slicer Settings

The software used to prepare the printer code varies greatly depending on whether the printer uses resin, extruded material, or layers of powder/sand solidified by lasers or binder. For slicing with resin-based printers (SLA and DLP) UV duration and intensity settings will be determined based upon the resin. The aspect of this method that requires skill is positioning the model and generating supports for the model. As AI (Artificial Intelligence) software is optimized for predicting areas where supports are needed, this will become easier. For FDM printers code is generated to control the extruder/fan settings and every aspect of its movement. Layer height and line thickness determine the detail of a part while infill and wall-layer thickness determine the strength of a part. Depending on the material, the print speed, material flow, extruder nozzle heat, and fan settings should be adjusted. Powder and sand-based printers operate similar to resin printers with the major difference being that no supports are needed due to unsolidified or unbonded material acting as a support, though the model will need to have open gaps to allow unsolidified or unbonded material to flow out.

3. Printer Capabilities and Cost

3.1 Low Complexity, Low Quantity

For most hobby grade/ small shop printers prices range between $100 and $2,000 USD. Printers in this range typically have a build volume of 200mm x 200mm x250mm but can exceed 400mm x 400mm x 450mm for large build plate FDM printers. These printers typically utilize plastic filaments or resin in the case of DLP. Additionally, these printers can have surprisingly high precision when correctly tuned and utilizing effective print code. These printers are best used for small to medium-sized parts made from easily printed materials with easily achievable tolerances (0.1mm).

3.2 Highly Specialized, Medium Quantity, Small Total Volume

The next step up from hobby grade printers are professional printers. These printers’ range in price from approximately $1,200 to $25,000 USD and are characterized by their ability to print with extreme precision, ability to effectively utilize composite materials, and significantly larger build volumes. These printers consist mostly of large FDM printers that can have multiple extruders capable of printing composites with exceptional strength, hardness, and thermal resistance. Having multiple extruders allows for the use of easily removeable or dissolvable supports which allow for more complex geometries. Resin Printers in this range consist of large volume SLA printers known for their ability to create large parts with tight tolerances.

3.3 High Complexity, Low Quantity

After professional printers, the next tier is industrial printers where investment prices range from the tens of thousands to millions of dollars. These printers are highly specialized for heavy industrial uses and niche processes. A significant portion of these printers utilize multiple lasers to solidify powered metals or ceramics with extreme precision over a large build size. Other large industrial printers have large build volumes (in the multiple cubic meter range) allowing for SLA printing of large patterns or entire investment casting trees. Lastly MultiJet printers fall into this category, with extreme precision of print quality, ability to create geometries with dissolvable supports, and a variety of specialty formulated materials.

4. Printing with FDM

4.1 Available Filaments and Their Effectiveness

Historically, investment casting has relied on wax as the primary material for creating expendable patterns to make molds from. It is important to note for FDM the majority of PLA filaments can be used with minimal ash residue. There are already various materials on the market for both filament and resin printers that are wax composites designed to be burned out for the creation of an investment casting shell. Many filament companies are advertising ash-free burnout filaments. Upon testing, these parts are comparable to standard PLA leaving around .021% ash residue [6]. This remaining ash is still enough to warrant a secondary cleaning step which adds an extra day of drying to the process.

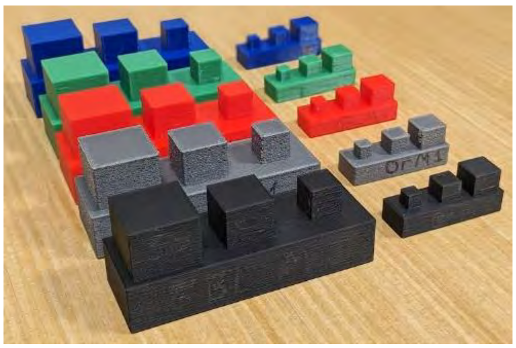
4.2 Popular FDM Printers

Out of all methods of printing discussed in this paper, FDM printing is the most well established and widely used. FDM printers are widely available and considerably cheaper than the other methods. Basic PLA plastic filament costs an average of $20 USD per kilogram (kg) and a specialty formulated wax filament designed for investment casting can cost up to $128 USD per kg [7]. A suitable, low cost FDM printer will cost under $500 USD. Some examples of the most popular printers in this range are Creality, AnyCubic, and Flashforge. When properly maintained these printers will be suitable for low volume parts (parts that fit within 200mm x 200mm x 250mm). Depending on the desired size of the printed pattern, these brands have models of printers with build volumes exceeding (400mm x 400mm x450mm) for approximately twice the price of standard models. For operators that are newer to 3D printing or companies that wish to have more reliable printers which require less maintenance and tuning there are several more premium brands utilized in professional and research settings. Currently some examples of well-established brands in this market are Prusa, Stratasys, Utilimaker, and Makerbot. These printers can cost anywhere from $1000 to $5000 USD. While these printers are significantly more expensive than most hobby grade printers on the market, they are typically much easier to operate and significantly more consistent with their prints. Compared to resin-based printing, FDM printers are much easier to integrate and learn due to how the files are processed as mentioned in section 2 and are significantly cheaper in both initial capital cost and material cost.

4.3 Solidification Shrinkage in Filaments

Another obstacle to the widespread use of filament-based printing for investment casting is the slight shrinkage that occurs in printed parts. The investment casting process is long known for its ability to cast for tight dimensional tolerances and a quality surface finish. It is important for investment casters integrating low-cost 3D printing in house to be able to easily access the shrinkage correction factors for their specific printing process, feature sizes, and material to be able to achieve a satisfactory print. This is one area of research that is currently being explored. An online tool to address this design constraint is being developed by the authors to help investment casters more easily integrate low-cost 3D printing. On average this shrinkage for filament-based is approximately 0.9% [8]. Figure 1 below shows sample 3D printed test artifacts, where each set of artifacts contains 7 unique features to be measured while two sets of artifacts were printed and repeated on two printers of the same make and model, giving a sample size large enough for statistical significance. From the analysis of dimensional error across filaments, it was found that error is more dependent on the filaments used rather than the dimension of the feature measured (Table 1) [8]. Utilizing dimensional data collected via a dimensional test artifact, the dimensional shrinkage can be calculated as a percentage of the geometry size by carrying out the regression analysis of error from the measured part value to the nominal value

(Figure 1) (Table 2). By taking the inverse of this slope value, an adjustment factor can be calculated to offset the shrinkage of the printed parts. Additionally, the R-squared value calculated can be used to gauge the reliability of the adjustment factor and the dimensional consistency for parts printed with the filament (Figure 2) [8]. Looking at the results of the regression analysis for PLA filament in Table 2, it was found that using the slope of the regression line, an approximate adjustment scale factor of 100.755% can be used in a slicer to offset filament shrinkage.



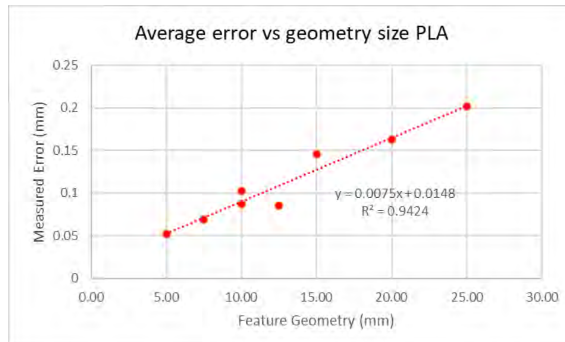


Figure 1 (left): 3D Printed Test Artifacts.
Figure 2 (right): Scatterplot of Dimensional Error vs. Geometry size with Line of Best Fit.

Table 1: Two Factor ANOVA Test Results Comparing the Effect of Geometry Size and Filament Used on the Error of Printed Parts.

Two Factor ANOVA test	Degrees of Freedom	Sum Sq.	Mean Sq.	F-value
Geometry	6	1.405	0.234	62.09
Filament	4	2.513	0.628	166.6
Residuals	629	2.371	0.004	

*Higher F-values (greater than the F critical value) are indicative of statistically significant differences in the statistical analysis.

Table 2: Results of Regression Analysis for PLA Filament.

	Coefficient	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.015	0.0060	2.4490	0.0156	0.0028	0.0268
Geometry	0.0075	0.0010	18.0100	0.0000	0.0067	0.0083

*P-values closer to zero (less than the significance level where α is typically equal to 0.05) are indicative of statistically significant differences in the statistical analysis or the identification of statistically significant predictors of the response variables.

4.4 Surface Finish of FDM Parts

In addition to shrinkage on printed parts, layer lines on the surface of the printed plastic part will show up in the final casting. This is another body of research that is being explored by the authors to help investment casters to be able to easily place low-cost 3D printers in service within the foundry while setting up the printer for satisfactory prints, meeting surface finish requirements for the printed patterns. For parts requiring a smooth surface, machining of the critical surfaces may necessary. To reduce the overall amount of machining, the surface roughness of 3D printed parts can be mitigated by keeping the critical surfaces closer to the build plate of the printer by properly orientating the model, and by placing the printer on vibration-dampening surfaces (Table 3) (Figure 3) [9]. Figure 3 below shows a chart of average surface roughness in micrometers across a range of distances of the printer from the build plate and the surface underneath the printer during printing. This data was collected from an object with a square 50mm by 50mm base and a height of 210mm by measuring the arithmetic mean (average difference between high and low points on a surface) parallel to the layer lines using a Mahr surface profilometer. Table 3 displays the results of the regression analysis carried out on the arithmetic average surface roughness (in microns) versus printing distance from the build plate.

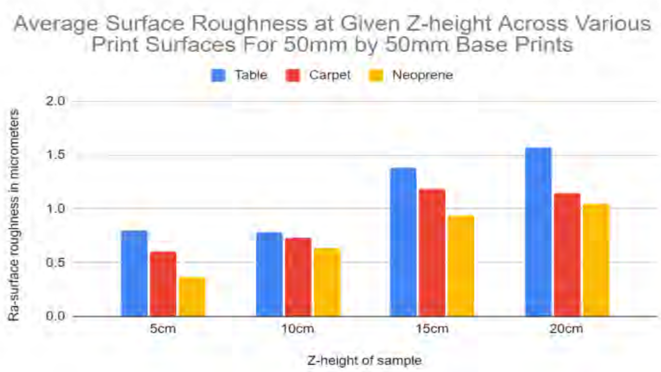


Figure 3: Chart of Average Surface Roughness.

Table 3: Results of Regression Analysis for Arithmetic Average Surface Roughness in Micrometers Versus Distance from Build Plate.

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	137.700	15.5050	8.8787	0.0000	106.200	169.200
Height from Base	1.727	0.4220	4.0942	0.0003	0.870	2.585

*P-values closer to zero (less than the significance level where α is typically equal to 0.05) are indicative of statistically significant differences in the statistical analysis or the identification of statistically significant predictors of the response variables.

5. Printing with SLA/DLP

5.1 Printing Ceramics Directly

Opportunities to 3D print directly with ceramic materials are being thoroughly researched for investment casting. Printing with ceramics would eliminate numerous steps of the process such as an initial die and wax patterns; and in return, costs and lead time would be significantly reduced. Unfortunately, the application of printing with ceramics for investment casting has not been mastered. However, there are some innovative technologies in this area to make printing directly with ceramics a key research area for investment casting moving forward. Specifically, there are numerous companies that utilize ceramic vat photopolymerization [3]. In essence, the process can be carried out utilizing an SLA or DLP printer and ceramic resins [3]. After the part is printed, it must be heated to create the final shell and final finish [3].

5.2 Production Rates

In recent studies, ceramic molds have been successfully produced as a complete design: pour cup, filter, sprue manifold and shell [8]. With the utilization of all components in one design and eliminating the need for tooling and wax molds, printing directly with ceramics has cut down the production time by a magnitude [10]. With traditional investment casting, customers can expect to wait for weeks or months for their casting to be complete. With this application of additive manufacturing, investment castings can be produced in as little as hours or days [11].

5.3 Cost of Resins

In terms of cost, 3D printing ceramic resins for SLA and DLP printers are more expensive than traditional photopolymer resins. Ceramic resins have additional ceramic powder and silica added to the material. Depending on the supplier, ceramic resins can cost from $130 to $400 for one liter of UV resin [12], [13], [14]. These resins are commonly compatible with both SLA and DLP printers. A notable ceramic resin is Tethon 3D's Castalite® Investment Casting Resin which costs approximately $400/L [14]. In addition to ceramic resins there is a wide range of resins designed to be burned out similar to PLA and wax composite filaments. Current prices for these resins range from $75 per liter to $290 per liter [15].

5.4 Post Print Processing

For parts printed on resin printers, whether they are printed in castable resin or ceramic resin, will require similar post-processing steps. The first step is the removal of the print from the build plate. After the print is removed, the supports used on the model will need to be separated. Most supports under 2mm (about 0.08 in) in diameter can be removed by hand. For heavy supports pliers should be used. After supports are removed the print should be bathed in a solvent bath (typically isopropyl alcohol) to dissolve excess resin stuck to the outside of the print. Depending on the resin and the complexity of the print, this will last anywhere from ten minutes to a couple hours. After the part is cleaned, any imperfections left from the supports can be sanded to ensure a smooth finish. Finally, the part should be exposed to UV light to finish curing the resin. The time and intensity of the light will vary based upon the resin used and the size/complexity of the print. When working with resin, it is paramount that there is adequate ventilation to prevent overexposure to fumes, as well as gloves to prevent skin contact as resin is a skin irritant [16].

5.5 Established Resin Printers

Although resin based additive manufacturing was developed before FDM based printing, DLP and SLA printers have lagged behind FDM printers in establishing a widespread audience, instead mainly focusing on expensive yet highly precise and specialized professional machines. Recently numerous DLP machines have become available at prices under $1000 USD. Some notable examples of these inexpensive machines are Elagoo, Anycubic, and Phrozen. These machines have relatively small build volumes (300mm x 200mm x 400mm) and can require some manual tuning. In terms of professional printers which utilize SLA technology, Formlabs, StrataSys, and 3D systems are established brands with extensive software and setup support, who have a multitude of wax and ceramic resins available. A notable startup in the field of ceramic mold printing is Admatech which is designing printers and formulating new resins for the purpose of investment casting mold creation.

6. Integration of Additive Manufacturing into Investment Casting Foundries

6.1 Determining Printing Process to Address Casting Requirements

Through conducting an internal review of order quantities and dimensional/surface requirements of prior castings the percentage of orders that would benefit from having their patterns produced via 3D printing or molds via ceramic printing can be determined by the investment caster.

Calculating the cost of 3D printing of parts will vary depending on the process used (see section 3 for more information). When unsure of what printing process to use for castings, sample prints can be ordered in a variety of materials and at a variety of specifications from various online 3D printing services. For the investment caster looking to integrate 3D printing into the foundry, this is one way they can compare processes and materials for their specific needs before they decide to purchase or lease machines for in house printing. To estimate the cost of 3D printing the patterns, the CAD models can be exported as 3D files into a free 3D printer slice software (Cura, PrusaSlicer, and ideaMaker for FDM are examples)). Using the print preview function, the mass of the print (usually grams) is supplied for FDM parts. PLA typically costs between $0.02 and $0.04 per gram. For resin-based printers, the same process can be carried out with a slicer software (Chitubox, Lychee, and PrusaSlicer for SLA are examples). Instead of providing the weight of the part, the resin volume (usually ml) is a predictor for the cost of the printed pattern. Typically, castable resin costs between $.07 and $.30 per milliliter. When printing molds with ceramic resin instructions for mold processing and design are provided by the manufacturer. For more expensive processes that are less widely discussed in literature such as MultiJet printing and ceramic printing, technical salespeople from the supplier companies can supply cost estimates as well as provide sample parts to assist in making an informed decision for the investment caster.

Using slicer software, the number of parts per print can be calculated as well as the time per print. With this information, the daily production rate can be calculated which can be used to determine the number of printers needed to produce the required number of patterns in the desired time frame for the investment caster. The specific printer to be used in estimation is mainly dependent upon the volume of patterns produced. It is paramount that the entire pattern fits within 90% of the printer's build volume. Additional research should be carried out by the investment caster to determine if speed, reliability, and printer precision is optimal or is a fit for the specific job types to be carried out.

To calculate the unit cost for 3D printing parts in house, a general estimate can be made using the cost of the printer, cost of maintenance, daily production rate, days of operation over a 3 year timeline, and the cost of consumables (filament material). Based upon current market trends it is assumed current printers would be made obsolete by new technology in an average of 3 years. A general estimation for the cost of maintenance is 25% of the initial printer cost. This varies significantly by brand and type of printer. Accurate estimations for the maintenance cost can be found from available independent reviews of the printers. For both calculations, differences in electrical consumption, machine coding, and batch setup time between traditional and 3D printed processes can be assumed to be negligible. After calculating unit cost of various pattern types and what percentage of revenue these castings make up, potential savings from 3D printing patterns can be calculated and the decision on the specific printers to be purchased by the investment caster for producing patterns can be determined.

6.2 Creating Prototype Test Prints

Depending on what printers are found to be a good economical and product size/ accuracy fit for the foundry, sample prints should be created with the in-house printers and the relevant materials. For lower cost printers, it is advisable for investment casters to procure a single unit and allow pattern engineers to learn the capabilities of the printer while testing out a variety of printer materials for its use. Ongoing research by the authors is being carried out to help investment casters integrate lower cost printers faster by providing online tools for optimal dimensional and surface finish printing. For higher end printers (typically printers whose costs exceed $3000 USD), it may be possible to request sample parts from the printer manufacturer. Using these sample parts, the investment casting process can compare these initial prototypes to previously made parts using traditional tooling. After creating mold trees and conducting burnouts, retained ash can be measured with various materials, to determine whether additional water cleaning is required (from work carried out by the authors, it is estimated this cleaning will add at least a day to the casting lead time).

6.3 Tuning of Print Settings and Selecting Optimal Print Material

After investment casters have integrated an additive process to a point in which castings meet or exceed specifications, experimentation can be carried out to reduce costs by tweaking the settings used to print parts, materials used in making patterns, or even using a less expensive machine/process (see section 2 for overview of slicer settings). In cases where an investment caster would like to further improve quality, light processing (quick sanding or smoothing with a wax coating or solvent to smooth layer lines) of parts can be carried out on areas of the print affected by removed supports or layer roughness. Additionally, the steps taken along with the tools being developed in section 4 can be implemented for FDM parts to improve surface quality and dimensional accuracy in the parts.

An extension to these methods of improving print quality and getting closer to a finished product with less process steps is going a step further to create prototypes for entire casting trees. If an entire casting tree can be printed to fit within the build volume of the printer, investment casters can capitalize with resin printers due to how they generate support material for their prints. In contrast, FDM printers will need to print support material which can be cumbersome for investment casters to remove and could potentially damage printed parts.

6.4 The Implementation and Scaling of Additive Manufacturing in an Investment Casting Operation

After the additive manufacturing skill sets have been developed and technology has been identified and proven to be able to advance the investment casting operations forward from a design and economic viewpoint, an additive manufacturing room for the investment caster can be invested in. For resin printers the facilities described in section 5.4 will need to be set up to ensure safe operation of resin printers. Additionally, printers will need to be operating in temperature and humidity conditions listed on material specifications. As additive manufacturing technology continues to evolve and as new data for operational costs of additive manufacturing becomes readily available, the true effectiveness of evolving 3D printing workstations can be determined, and revised calculations of the specific components and designs suitable for 3D printing can be conducted. Based on the results of these calculations a decision can be made to reduce the daily capacity of the printers within the additive manufacturing space or increase their capacity through purchasing additional or larger machines to expand into new part sizes or designs. In addition to adjusting printing capacity, the ability to create unique printed geometries can be advertised to customers and research can be carried out to demonstrate enhanced geometrical capabilities of newly developed and adopted processes. Figure 4 shows an estimated timeline for the low-cost additive manufacturing integration in an investment casting foundry operation. A similar integration of FDM printing for investment casting was carried out by the authors on a lab scale for experimental and prototype components. The main factors in determining the exact phase integration time will likely rely more upon the specific process being used in printing and the precision and consistency required by the patterns selected by the investment caster.

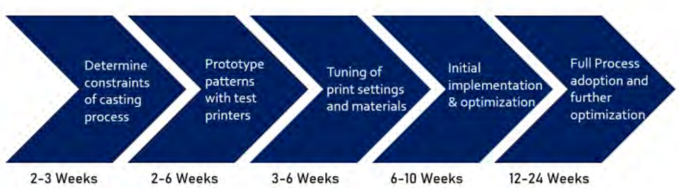


Figure 4: Estimated Timeline for Low-Cost Additive Manufacturing Integration in an Investment Casting Foundry Operation.

*Timeline was constructed with the assumption that design and process engineers are new to 3D printing and need time to develop and adapt additive manufacturing skill sets as the technology is implemented. Time phases are estimated by lead times for machine & material delivery as well as multiweek online printing courses and conducting multiple iterations of test prints.

7. Summary, Conclusions, and Future Work

Based on the areas of additive manufacturing researched in this paper, it is evident that 3D printing has an important place in the current and future landscape of investment casting for rapid prototyping of casting patterns, production of casting patterns for unique or low quantity casting orders, and creation of both injection wax molds as well as ceramic molds ready for casting. Even though many different forms of printing exist, an array of these printing processes when utilized for the proper production needs have the ability to save investment casting foundries money and time through replacing the need for hard tooling and reducing lead time. Figure 5 below summarizes an array of printing technologies and demonstrates how each can be utilized in investment casting operations along with pros and cons of each process.

FDM	DLP	SLA	Ceramic Resin	Multi Jet
Use: Prototyping Pattern Making	Use: Prototyping Pattern Making	Use: Prototyping Pattern Making	Use: Mold Making	Use: Prototyping Pattern Making Mold Making
Pros: Low Costs Ease of Adoption	Pros: Low Costs High detail	Pros: Ultra Fine Detail	Pros: Significantly cuts lead time	Pros: Ultra Fine Detail Multi Material Printing
Cons: • Rough Finish • Slight Shrinkage • Dimensional Accuracy	Cons: • Resin safety concerns • Generation of part support material	Cons: • Resin safety concerns • Generation of part support material • High Price	Cons: • Resin safety concerns • Generation of part support material • High Price	Cons: • Resin safety concerns • High Price (both machine and material wise) • Very High Price

Figure 5: Summary of Various Printing Technologies.

While there are implementation barriers including initial costs, gaps in worker skillsets with additive manufacturing technologies, and understanding additive manufacturing design rules to meet investment casting requirements, these can all be overcome with innovation and training. As technology continues to advance, printers are becoming more affordable. The main barrier currently to overcome is a lack of additive manufacturing skill sets in the traditional casting process workplace. The roadmap for increased integration of low-cost additive manufacturing directly into the investment casting foundry is multi phased and is poised to rapidly change over time in terms of both process and material types being used. Figure 6 displays a technology implementation flowchart developed by the authors that demonstrates how low cost FDM printing using PLA is ripe for implementing additive manufacturing into current investment casting operations and as skill sets, printing technology, and materials develop over time, directly printing investment casting shells and cores will become widely adopted.

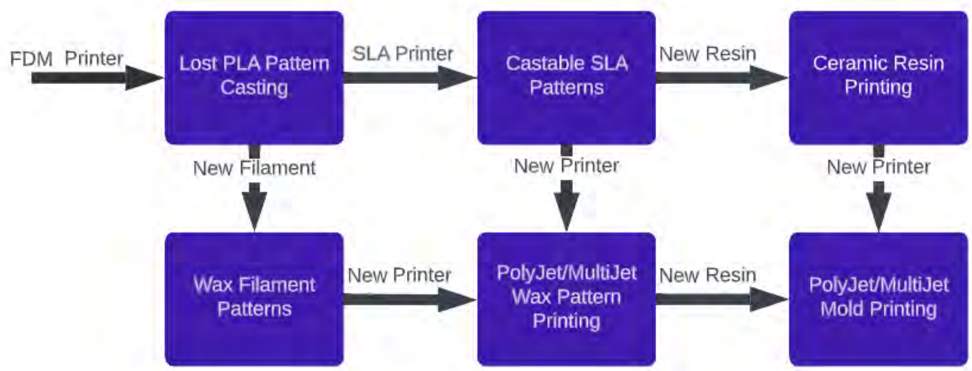


Figure 6: Technology Implementation Flowchart.

At the current time, the continued research outlined in this paper on the development of easily accessible dimensional and surface finish design guides will make it increasingly easier for investment casters to successfully integrate low-cost printing in house. FDM printing with PLA is a low-cost technology that can be easily implemented into the existing investment casting operation. In the near future, the plan is for research to be carried out by the authors to create an online tool for calculating the dimensional error from user input data collected from the print artifact mentioned in this paper. In addition to outputting an adjustment factor along with a diagnosis about how reliable the printer and material were for printing dimensionally consistent parts, the plan is for this site to compile the data and compare the user data to the population of prints done with the same filament and printer in order to gauge the affect individual machine conditions or controlled print parameters have on dimensional accuracy and part strength. Next, as investment casting foundry personnel become increasingly trained in additive manufacturing and their skillsets and design knowledge adapt, the implementation of low-cost additive manufacturing into the traditional casting foundries will be increasingly more common. In terms of future work, after initial work was completed by the authors on integrating lower cost additive manufacturing for investment casting, the authors identified an additional item for future work to help investment casters: determining the optimal infill and wall thicknesses and the effect infill and wall settings (print density control) have on retained ash and likelihood of burnout mold failure.

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INVESTMENT CASTING INSTITUTE

How Is My Pattern Coating & Draining?

Gavin Dooley
REMET UK

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 3

HOW IS MY PATTERN COATING AND DRAINING? APPLYING THREE INTERVAL THIXOTROPY TEST (3ITT) IN DETERMINING THE STRUCTURAL DEFORMATION AND RECOVERY OF INVESTMENT CASTING SLURRIES

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Abstract

A novel method of studying the rheological behavior of ceramic slurries for investment casting using the three interval thixotropy test (3ITT) technique is being used for the first time to determine the effect of instant shear on the structural deformation and recovery of slurries. The technique is of potential importance in the investment casting industry and could be used to fingerprint different types of slurries based on their rheological characteristics. In this study, several investment casting slurry products were instantly deformed with predetermined levels of shear stress and shear rate which attempt to simulate forces at play during application of a slurry onto a wax pattern.

The 3ITT data revealed that the applied instant shear resulted in deformation of the slurry samples to different extents depending on slurry type, shown by their deformation which in turn resulted in different durations required for structural recovery.

In conclusion, the results demonstrated that 3ITT is an effective method for the collection of data on deformation and structural recovery kinetics of investment casting slurries, and therefore is an effective tool for simulating and analyzing the effects of the handling, stirring, and dipping steps relevant to the application of investment casting slurries onto wax patterns

Introduction

The 1st coating of your wax pattern is arguably one of the most important steps of the PIC process. It is the first point in the process which remains an unknown until the shell is removed and the casting is cleaned. It is typically the highest cause of scrap defect within the foundry and can cause many costly scrap parts.

One aspect of the coating cycle which has been previously explored was the wetting angle or surface tension of the slurry (1). This work was presented previously in 2019 as part of a body of work examining the phenomena of coating wax patterns. The results gave us interesting results on the influence of surfactants in slurry mixtures. As can be seen in Figure 1, the amount of slurry retained on a plate after 150 seconds was different based on the presence of a surfactant.

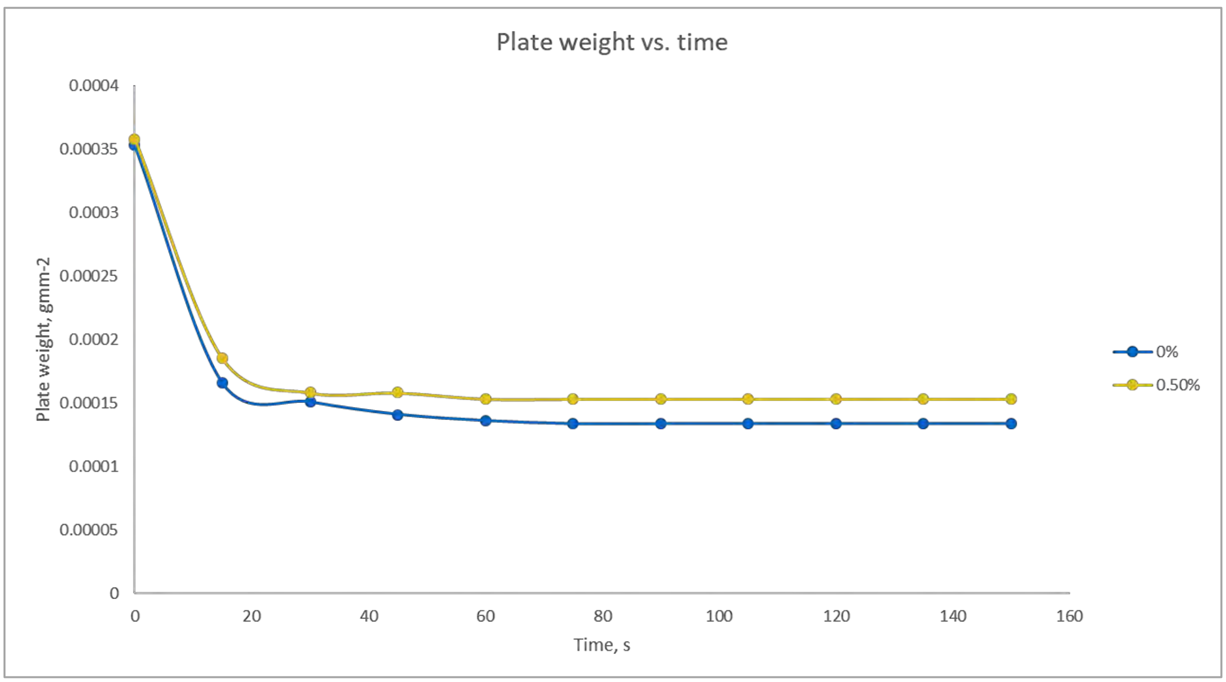


Figure 1 Effect of plate weight on slurry samples with and without surfactant (1)

As presented in various literature, there exists a link between, viscosity, surface tension and the reaction of the material to various stresses (2).

The viscosity of investment casting slurries is a key property for the control of your process. Papers presented at recent conferences have highlighted the need for improved methods of measurement and training when it comes to viscosity measurement (3).

Within the industry, flow cups remain the fundamental viscosity measurement technique. Despite various efforts to automate (4) or measure via more advanced methods have fallen short in becoming the industry standard. This paper does not attempt to replace current viscosity measurement techniques, but presents a laboratory technique to analysis how a slurry behaves in different stages of the coating process, most importantly during draining.

This paper presented results of a new viscosity measurement technique which was utilized within the REMET lab to assess how the slurry will coat a wax pattern under high shear conditions, and drain under low shear conditions to produce a strong and reproducible prime coat.

Materials and Methods

There are various different levels of flow within all materials, ranging from ideally elastic solids like steel to perfect liquids like water as exhibited within Figure 2.

Figure 2 The flow of materials from water to steel

For PIC slurries, we are dealing with non-Newtonian fluid which display both liquid and solids phases due to the presence of liquid like colloidal silica and polymer, and high refractory loading.

For this study, an Anton Parr® rheometer was utilized within the REMET UK R&D facility. Typically used for temperature dependent rheological measurements of waxes, the equipment has the added capability of measuring liquids. This was achieved by using disposable aluminum pans and alternative spindle configurations as seen in Figure 3.

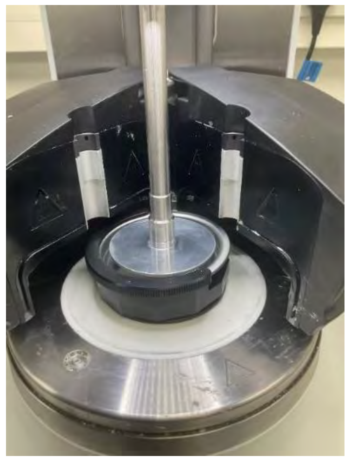


Figure 3 Experimental setup with disposable dish and replaceable rheometry plate

The three interval thixotropy test (3ITT) technique is being used for the first time to determine the effect of instant shear on the structural deformation and recovery of slurries. 3ITT examines the rheological response of a material at three different intervals :

- Interval (1) Very low shear to simulate behavior at rest at a preset low shear rate
- Interval (2) Strong shear to simulate structural breakdown of the sample during the coating process at a preset high shear rate, for example when applying paint with a brush or by spraying,
- Interval (3) Very low shear to simulate structural regeneration at rest after application using the same preset low shear rate as in the first interval. Usually, the result is presented as a time-dependent viscosity function (Figure 4):

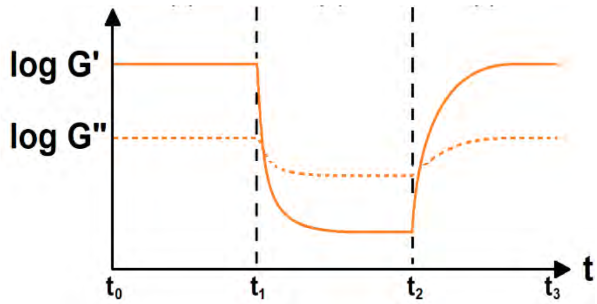
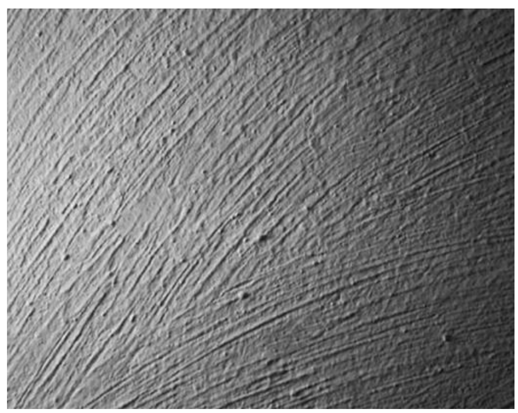


Figure 4 The 3 ITT testing output

The results present two datasets, G' (Storage modulus or "G prime") and G'' (Loss modulus or "G double prime"). The elastic modulus measures the amount of stored structure which exists within the material. As the shear rate increase within the second interval ($t_1 – t_2$), the material loses structure and the viscous property of the material, represented by the G'' is dominant. Finally, as the shear rate is removed from the sample, the storage modulus recovers, and the material will act more solid like after a certain time between t_2 and t_3 (5).

This test is adopted from the paint industry where the 3 ITT best represents what is happening at the point where the paint is applied to a wall, and the shear is removed. If the recovery is too slow (Figure 5 a) there will be a sagging of the paint on the wall. If the material recovers too fast (Figure 5 b), the paint brush strokes will remain behind, leaving a poor finish.

(a)

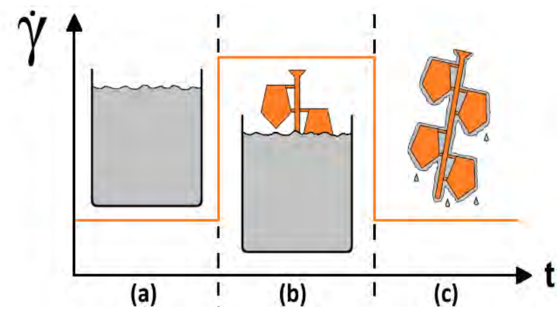


(b)

Figure 5 The different structural recovery of materials will have an effect on the final flow and finish of the coating on the surface. Shown here is the effect on painted surface of (a) slow recovery leading to sagging and (b) too fast, leaving poor levelling

We have represented this at three stages:

1. The slurry mixing in the tank – While there is some high shear inflicted on the material due to the tiller, the center of a tank is at near rest
2. Dipping of the pattern into the slurry will
3. Finally, the draining of the material over the tank has extremely low shear rates, and is represented in the third interval.



Below is the standard formulation used.

Table 1 Slurry recipes used within the study

Component	Tradename	Standard Slurry [g]	Slurry without polymer [g]
Colloidal Silica	Remasol® SP30™	350	400
Refractory	Fused silica #200	700	700
Polymer	AdBond® Ultra™	50	-
Surfactant	Victawet 12	10	10
Anti-foam	Burst 100	2.5	2.5

Below are the settings used on the Anton Parr rheometer. Based on literature available, it was deemed 100s^{-1} was an appropriate shear rate for the dip coating application. The test procedure used an oscillation- oscillation- oscillation test scenario for the intervals throughout the work.

Table 2 Experimental setup of rheometer

Interval	Shear Strain (% Osc)	Frequency
Interval 1 (1s-120s)	0.1	1
Interval 2 (120s-240s)	10	1
Interval 3 (240s-540s)	0.1	1

Results and Discussion

Is my test repeatable?

Firstly, as with all experiments or test methods we generate within REMET UK, we always assess the amount of error or repeatability we have between samples measured via the new method. Figure 6 shows a comparison of 3 tests carried out on the same material made up three different times and measured on the Anton Parr rheometer.

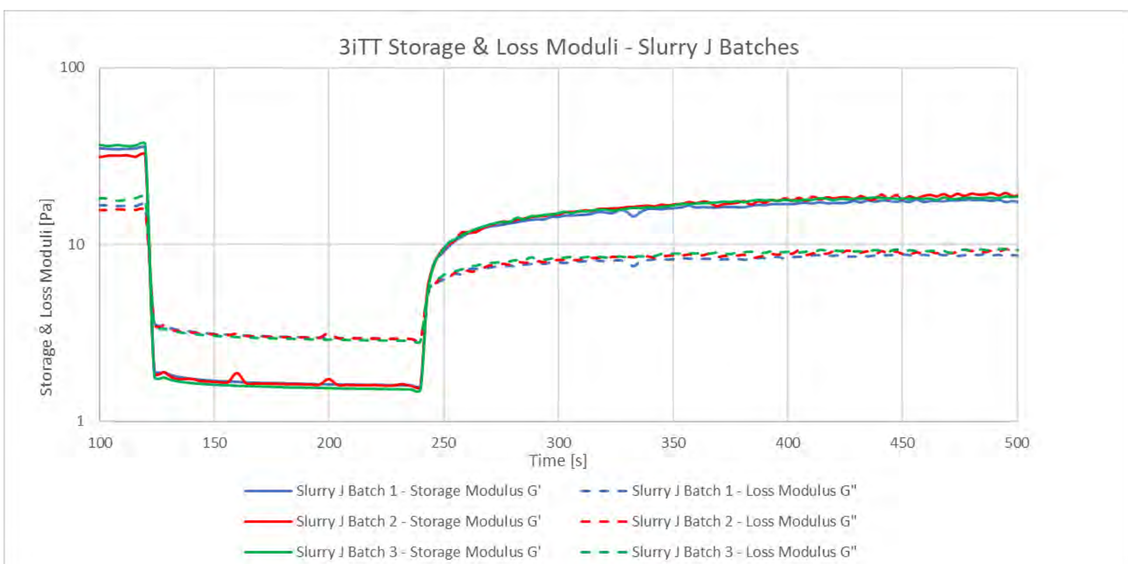


Figure 6 Three tests carried out on a slurry to assess the repeatability of the test method

What does a standard slurry look like?

First material we looked as was a standard slurry of colloidal silica, polymer and refractory. Within the first interval, a steady state viscosity is reached whereby the slurry is lightly sheared to maintain suspension of the refractory. Within the second interval, the shear is increased 100 times. During this phase, it is clear the G' storage modulus is prominent, indicating the slurry as acting more like a liquid within the slurry. Finally, as we reduce the shear to 1/100th shear of interval 2, we can see the recovery of the storage modulus.

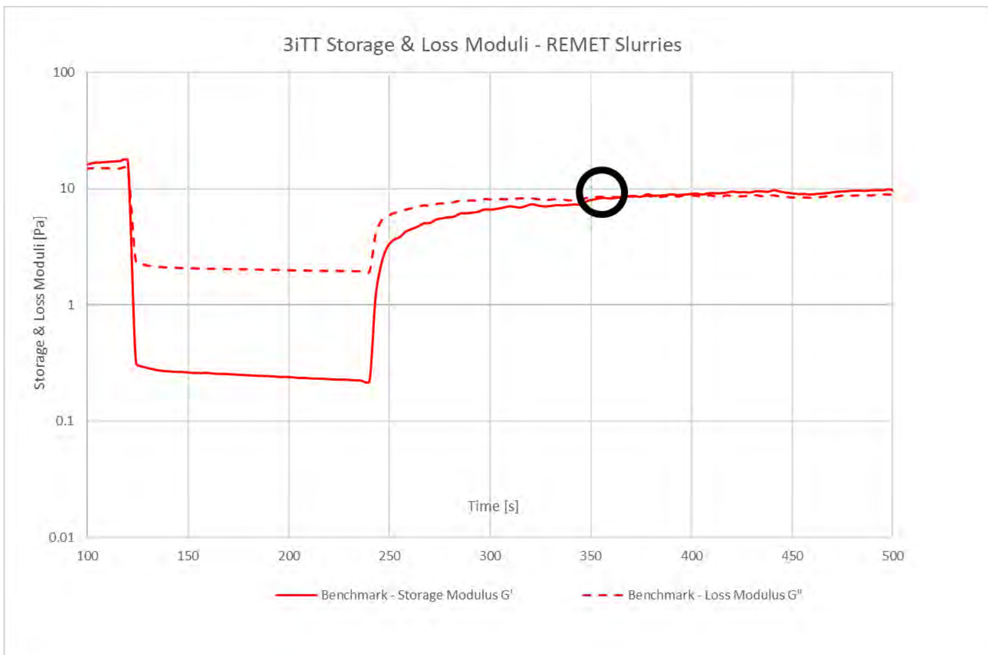


Figure 7 Standard slurry under 3ITT testing regime

During our analysis, we were also carrying out studies on a new polymeric material which we felt might aid in the strength development of the shells. While we were dipping the materials, we noticed extended draining times with similar viscosities measured on a Zahn cup than our standard slurry. As within Figure 8, it was shown the recovery of the storage modulus was longer than a traditional slurry, which explained the difference in rheological properties of the new material.

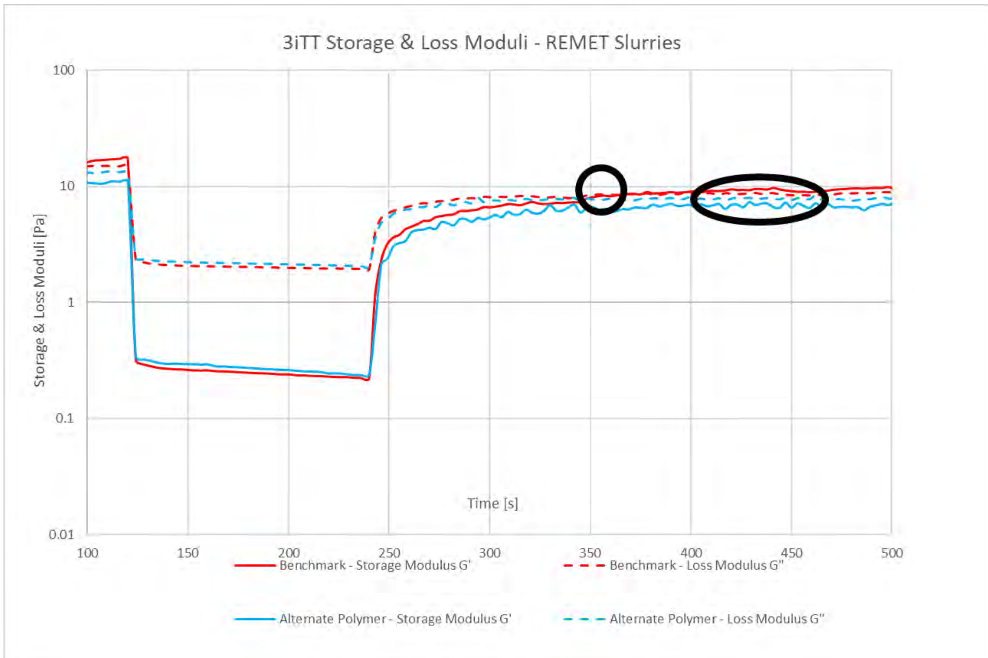


Figure 8 Comparison of a new polymer which exhibited extended draining times during draining. It was found the recovery of storage modulus was later than standard slurry, for a comparable viscosity.

Within Figure 9, it can be seen a slurry without the presence of a polymer will influence the flow characteristics of the slurry. Without a shear thinning and recovery of the polymer, there exists an extended draining process which will influence the coating thickness laid down by the slurry.

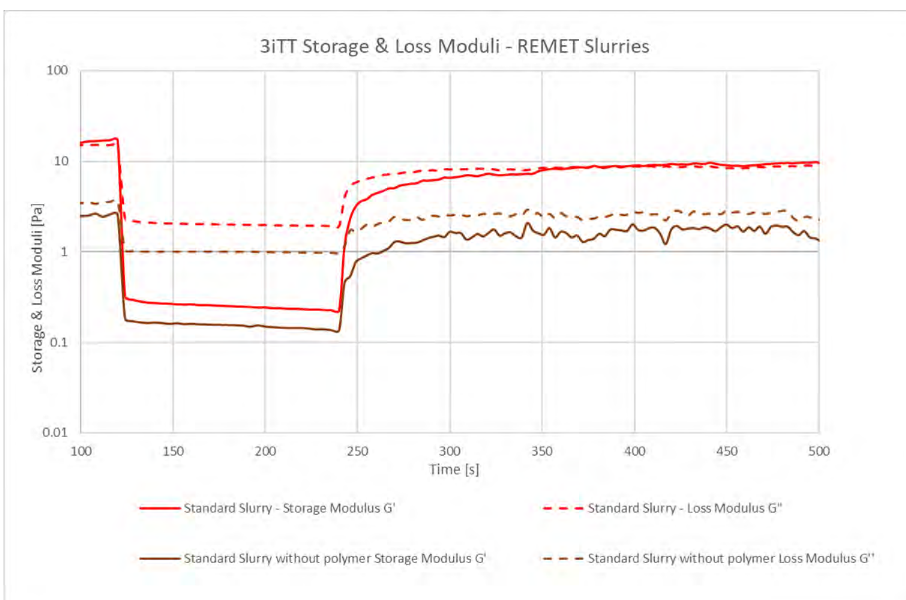


Figure 9 Comparison of standard polymer with slurry without the polymer present

This result explains why typically the presence of polymer can increase thickness within a shell system.

Case Study

A European foundry was struggling to build shell thickness due to various different shell room issues resulting in autoclave cracking. Their incumbent system was a polymer enhanced slurry and rainfall sanding was used as the stucco application method throughout. When the material was sectioned, it was clear that the thickness on edges and curved surfaces was very poor.

To remedy the situation, Remasol® QuikBuild™ was proposed as a solution. The material was tested alongside the standard slurry and is presented below.

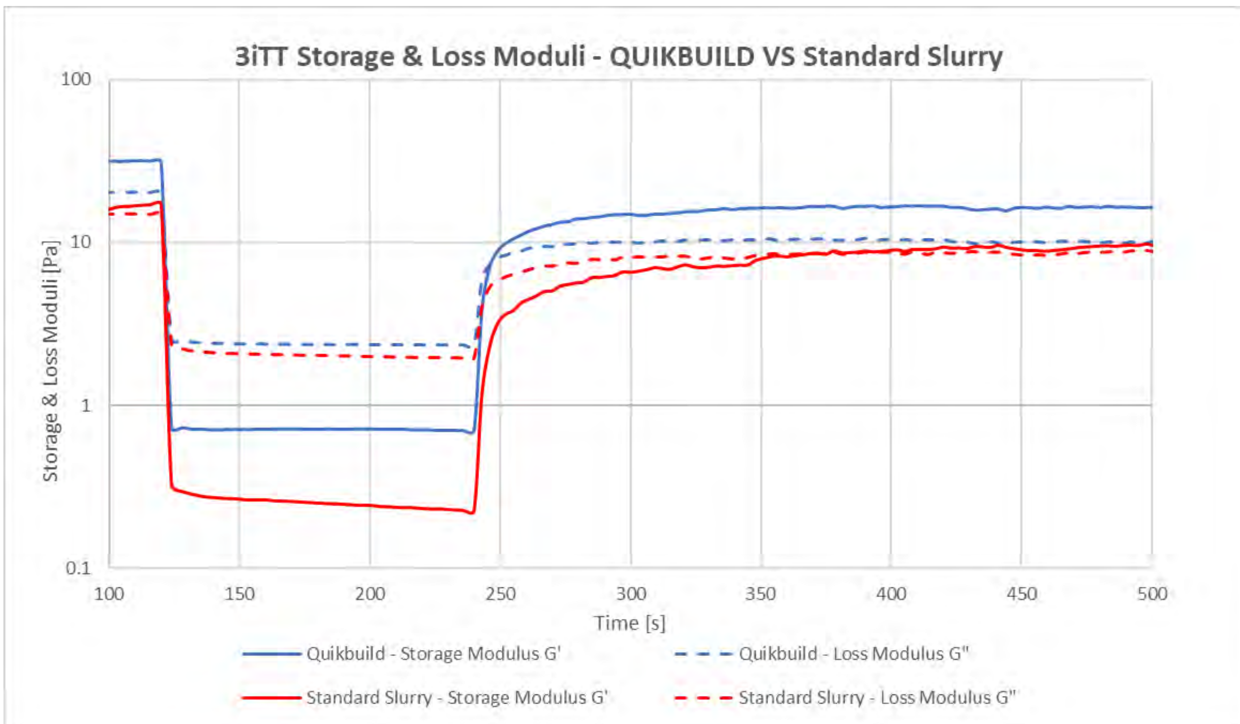


Figure 10 Comparison 3ITT for standard polymer enhanced shell system versus Remasol® QuikBuild™

Within the figure during the high shear, interval QuikBuild exhibits similar liquid phase rheology (G’’) to a standard slurry. As can be seen, there is a much quicker recovery of the material to a solid phase than a standard slurry, this means the material will recover and create a thicker slurry layer than traditional layers.

In practice, this proved to be the case as we progressed with the trial. The Remasol QuikBuild replaced the standard binder, and the same Zahn cup viscosity was established. The results of the can be seen in Figure 11.

Standard Slurry ***Remasol® QuikBuild™***

Figure 11 Comparison of shells built with standard polymer enhanced slurry and Remasol® QuikBuild™ slurry system

There is an average of 15-36% weight increase on the shelled materials. This is presented in Figure 12.

There was a significant reduction in scrap issues due to the implementation of the new slurry system. .

The customer also had no issue with still measuring polymer & silica content within the backup slurry.

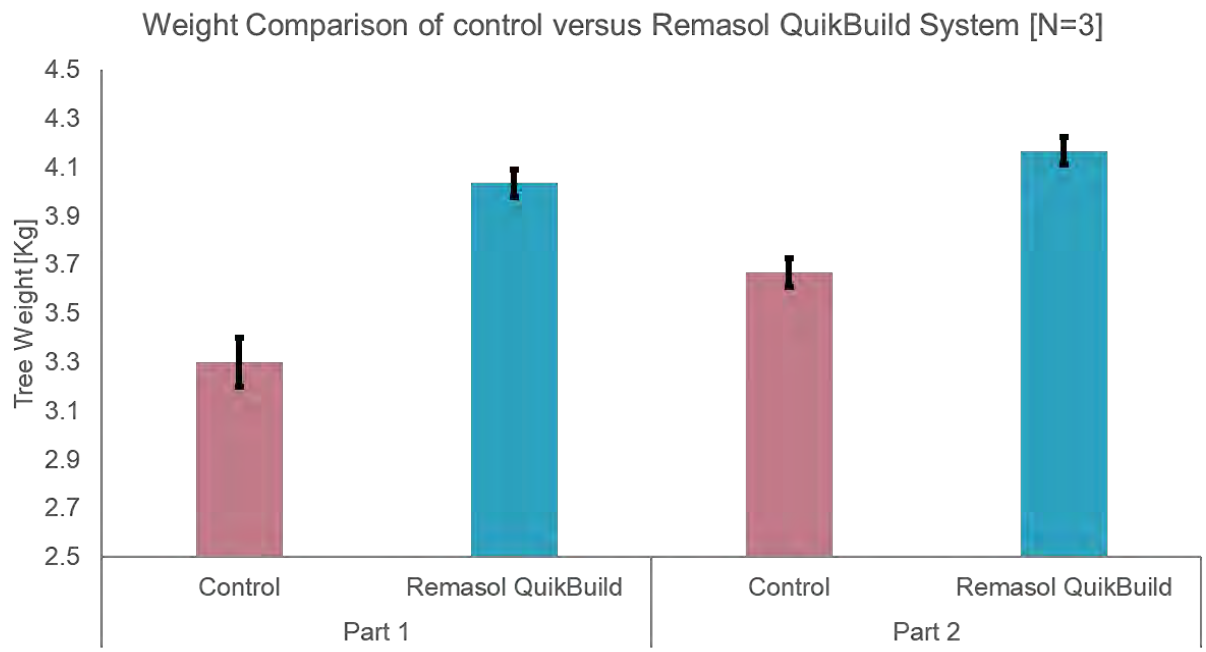


Figure 12 Comparison of shell weights of standard shell system and Remasol® QuikBuild enhance binder

Conclusion

3 ITT testing can assess the draining characteristics of various slurry configurations. The presence of the polymer additive within the slurry acts as a shear thinning material which recovers during the draining cycle to ensure an even coat is achieve on the pattern. By utilizing the knowledge gained by the test, REMET have developed a slurry which can recover quicker than traditional polymer-based shell systems to ensure a thicker coat is applied to the shell to reduce the number of layers required.

The Remasol® QuikBuild™ system has been proven within the industrial environment to allow for increased weight of shell in less coats to increase robot capacity and create stronger layers when compared to traditional slurry systems.

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INVESTMENT CASTING INSTITUTE

Training & Recruiting High-Quality Next Generation Through Industry Partnered Competitions

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70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 4

Training and Recruiting High-Quality Next Generation through Industry Partnered Competitions

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Abstract

Communication between students and industry in engineering programs is typically very limited if existent at all. A new competition with a new model has emerged where students interact directly with foundries as part of the process. This paper describes that process along with the benefits for students and companies involved.

Introduction

Industry partnered competitions consist of student teams working with a company to develop and execute the contest entry. While student competitions have existed for a while, industry generally is on the sidelines, typically as sponsors, judging, or providing advice. Otherwise industry involvement has been low. A new competition (well, 5 years old) has used a new model that requires the integration of the student team working with a specific company in industry. This competition is particularly of interest to Investment Casters as this has been the casting process of choice for student teams.

Cast In Steel (CiS)

Cast in Steel is a competition that challenges university students to use modern casting and design tools to creatively design and produce a designated functioning artifact. These artifacts are historical in nature but they allow for engineering design, design for manufacturing, tooling production, production and finishing. The artifacts have to be functional as they will be tested for performance. Other judging criteria include Artistry, Quality of Engineering Processes and Report (Including testing videos), Team Effectiveness, etc. Past artifacts have included:

- 2019: Viking Axe
- 2020: Bowie Knife
- 2021: Thor's Hammer (figure 1)
- 2022: Celtic Sword
- 2023: African Spear Point

Figure 1: Thor's Hammer Competition Entry

General Process

The student team is paired up with a foundry that will provide expertise and eventually produce the article in question. Typically, the students will come up with a design for their article and material selection. They will then work with the foundry exploring capabilities of the process vis-à-vis their article, available options for alloys (that is, what alloys does the foundry actually pour), requirements for tooling, etc. Then they will develop the process with the assistance of the foundry, produce 3D printed patterns or molds, the foundry will typically assemble the final tree/pattern and create the mold, pour the casting and sometimes heat treat the casting. This is then given to the students to finish. Depending on the capabilities available to the foundry, they may also perform NDT, dimensional inspection, etc. but these are not essential. The following process description is an ideal process, which as foundries we are aware it does not flow this easily. Especially when working with students some of whom this will be their first casting and industry interaction experience.

The students are rated on the effectiveness of their design vis-à-vis performance tests, artistry, and historical accuracy. The competition provides significant flexibility by only establishing certain boundaries such as maximum length and weight. Otherwise, the designs are wide open. With regards to performance, as an example, swords are required to cut articles and retain their sharp edge. The tests performed are dependent on the article produced.

The students are expected to perform significant research and justify their design on a historical basis. For instance, for the Viking axe, while there is significant variability there must be a line that connects the submitted design with original artifacts. Then, the artistry and aesthetic component comes into play. The students can choose from many options to make the artifact stand out with the overall design (see Figure 2) even if it is an artistic deviation from the original historical artifacts. In other instances, the students can incorporate other features such as those shown in Figure 3 in the Viking Axe. In this case, the runes incorporated have a historical connection.

Figure 2: Celtic Sword showing an aesthetic choice in the grid pattern within the blade

Figure 3: Viking Axe with runes incorporated in the blade and handle as artistic elements.

The design of the artifact has to incorporate the fact that the geometry must be cast. The bulk of the geometry is meant to be cast with some secondary processes allowed, such as grinding for sharpening, polishing, or finishing within the hole for handle fitting. This is where the interaction with foundries begins. Students will often design parts that are not castable. This can be due to inexperience as some contestants have not taken casting courses yet or because they do not fully grasp the details of what will make a successful casting. At this point the foundry will provide feedback to the students so they can modify their design to eliminate uncastable features, modify the design so they become castable, and learn more about the process on other items where they can incorporate features assumed as not being castable. This entry design process takes many forms, but in general it includes CAD design, communication with the foundry, casting filling and solidification simulation, if possible site visits to the foundry by the team.

As part of the design process an alloy must be selected. Here the students will typically research possible alloys that will meet the function based on their research. Sometimes, they will have alloys that are not commonly cast such as 1060 steel, or under optimize by over emphasizing criteria. For instance 316/CF8M stainless steel for corrosion resistance, but it does not really hold an edge. This is another area where working with the foundry exposes students to the reality of industry. First off, what suitable alloys does the foundry pour? This typically simplifies the conversation, and the student learn. For a sword, a martensitic of PH stainless was often a common choice.

Once a design is finalized then the production process is designed. Investment casting has been heavily favored by teams because of the ability to produce intricate decorative detail but also, in the case of swords, the ability to produce a thin casting. It is worth mentioning that other processes have been used, primarily sand-based processes as will be described later.

Given the limited production runs, at a maximum about seven parts, one article for entry, one for the foundry, one for the school, and one for each team member (~4), permanent tooling is not used. Rather, 3D printed tooling is used. For investment casting the patterns are printed in available equipment with significant input from the foundry as to what will make a successful pattern (figure 4). The 3D printing has taken many routes: Students' home printers, school printers, company printers, and even company partners printers (at the request of the company to support the project at the discretion of the foundry). Information such as internal density, surface thickness, materials, etc. is the type of experience that the foundry will typically have that will help the students. Best practice has the students learning how to use the equipment and verifying settings for successful printing with test prints way before the patterns are to be printed.

Then the foundry typically takes over to use the patterns, assemble trees and produce molds. Then pouring, cutting, gate grinding and blasting take place. Some foundries will help with heat treatment if possible, some with edge grinding, but often the student team will have to find solutions to these issues if the foundry can't provide them.

Then the students have a rough casting and they work to finish it with polishing, fitting handles, additional decoration, etc. as the contest piece will require. The students will need to submit a detailed and professional report along with a testing video. The report will include team processes (organization, team responsibilities), design decisions, quality metrics, etc. The report is now limited to 30 pages due to the lengthy reports previously submitted.

Figure 4: 3D printed pattern.

The entries are then sent to the SFSA who coordinate and sponsor the contest. The entries are judged in several categories such as quality of engineering report, artistry, historical accuracy, etc. by a panel of industry experts. Then, the performance test has recently been done at the AFS Casting Congress, figure 5, and the final awards are given.

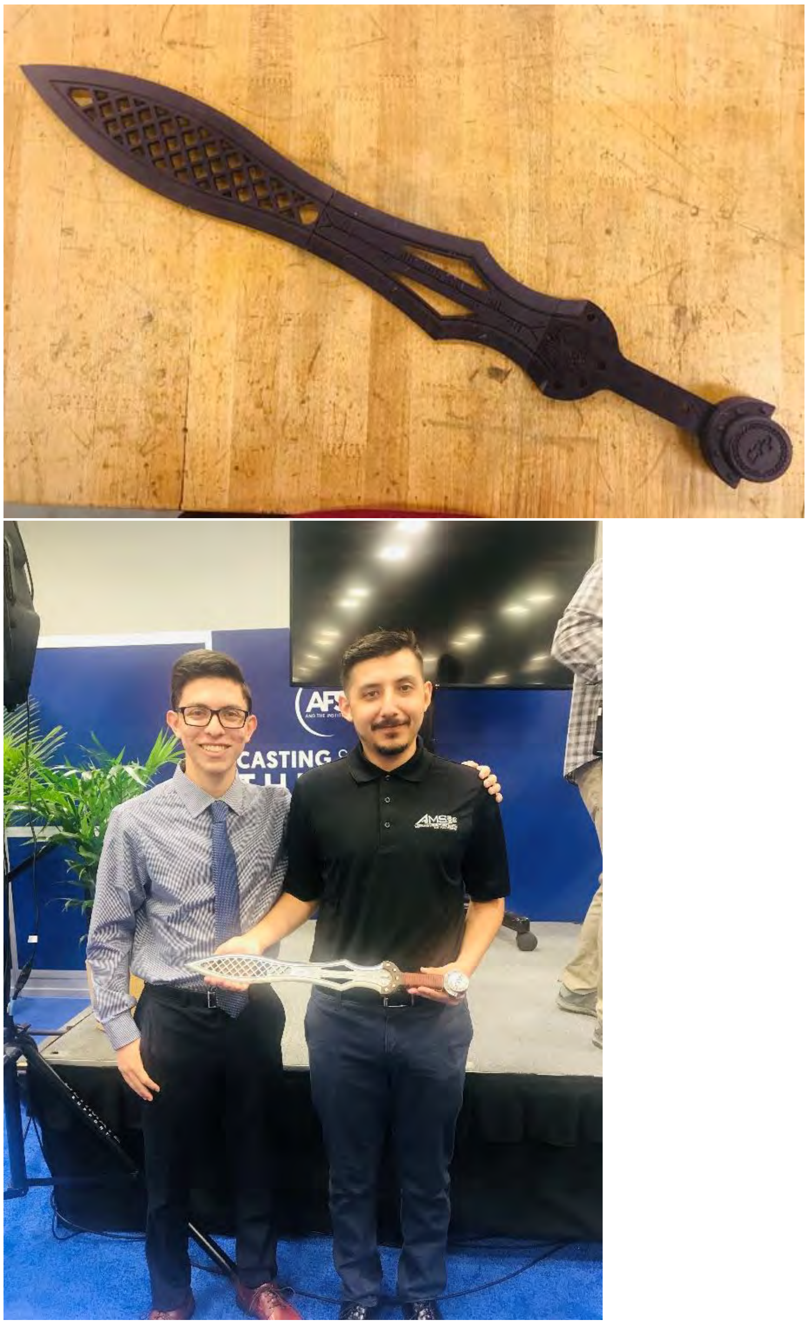

Figure 5: Students at AFS Casting Congress Competition and Final Judging

In the past typical processes have been investment casting with and 3D printed expendable pattern, patterns for sand casting, and 3D printed sand molds.

Challenges

Typical challenges have generally been due to the students' inexperience with real product development processes as well as communication. Among these, unrealistic expectations including improper or incomplete communication of expectations. This has gone both ways. For the students, they often do not coordinate well enough by not providing sufficient detail. From the foundry end, they assume that students understand 'obvious' things (obvious to people in industry, that is) so they forget to go the extra level of detail. Other simple things such as lead time or translated 'you can't expect the casting the next day after handing in a 3D pattern'; timely responses to inquiries by the foundry (that is, answer even if it is just an acknowledgment of the communication); formal communication and information sharing (not just texting). Other challenges, as discussed, over optimistic designs with features that are uncastable (too thin, too small, etc.).

Deadline meeting is a challenge that exists for the students. Many for the first time are faced with an open-ended project, with many internal deadlines which they often have to set and meet in coordination with their teammates. In addition, the have external deadlines, when does the foundry need your designs for review and patterns for production to allow them time to complete their tasks. This is one of the greatest contributions to the students development: project planning and execution.

Other challenges are team related. The first one is how to form teams. At Cal Poly Pomona we form teams that include upperclassmen and lowerclassmen, as well as students with casting experience (through work or classes) with newcomers, and students with experience in the contest with those without experience in the competition. Other schools may use other methods.

Other team related issues include lack of effective communication internally and with the foundry, unclear responsibility assignments, unclear expectations, missing internal deadlines, etc. One large problem is endless iteration of designs, that is they do not freeze the design at a proper time to move on to the next stages. Another is not taking advantage of processes that can be done in parallel and making them sequential, for instance, report writing while other activities are taking place. Also, not fully reviewing and learning the competition instructions and rules and sharing them with foundry partners.

Students will normally learn the importance of professionalism. After missing some meetings, or not showing up to the foundry as expected, or missing deadlines the foundry will typically report this to the faculty advisor to the team. Then, clear and forceful explanations are given, proper apologies are made (including a significant step up in performance as the only real proof of apology) and generally things work out. In the end, we work with industry to develop the students in all areas, not just technical knowledge.

Student perspective

What do the students get out of this? Meeting with industry and making contacts while getting closer to real world experience. Said another way, realizing reality: true capabilities, not textbook, what lead times are and why, expectations from industry, professionalism, soft skill development and understanding of its importance, project management experience, professional communication, teamwork and leadership, etc. Also, excitement and fun; professional networking; learn by doing; learn things that are not in class. Research – how to do practical research to address immediate problems; technical skill development (alloy selection, design, new processes, simulation, gating design, patternmaking, 3D printing, heat treatment, materials testing, NDT, etc.).

Foundry perspective

Why should a foundry participate? Fun. It is fun working with students despite occasional frustrations. In addition, it is very personally rewarding to see their growth through the process by helping educate students with a real world project and show the realities of working in/with industry. Other tangible benefits include exposing the next generation to casting; become actively engaged with the university for projects, guest speakers; screening for hiring; development of alternative solutions and selection processes; showcasing company and capabilities; etc. One common situation is that students, through their inexperience, sometimes question some things in the foundry which leads the foundry to learn and/or improve their processes in some areas.

How can a foundry participate if interested?

Contact the Steel Founder's Society of America (www.sfsa.org). If you have a local school that could be involved and you would like to work with them, introduce them to the contest. Currently, schools with four year engineering degrees have participated. However, this is a competition that is designed to be as open as possible and I believe that other student participants would be welcome, such as community college students.

Currently there is exploration on how to make versions of this competition available to high schools. At this time it is envisioned that the competition would be significantly different, but with the same objective: get students interested in metal casting through a compelling, fun and interesting project.

Conclusion:

The Cast In Steel competition allows students to design and manufacture an interesting and fun competition item. The competition is challenging at a technical, performance and artistic level. The students work directly with a foundry which provides benefits to both parties.

INVESTMENT CASTING INSTITUTE

Water Shell Removal Compared to Other Methods

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NLB Corporation

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 5

Water Shell Removal

Compared to other methods

Removing ceramic shells from investment castings without damaging the part can be a challenge, especially when high rates of productivity are demanded. Various methods are commonly used, and each has advantages and disadvantages. This white paper compares water jetting to the other methods and explores the key factors to evaluate when considering water jetting.

The metal casting process begins with the creation of a wax mold of the part. Multiple molds are usually combined on a "tree," allowing several parts to be made at the same time. This tree is dipped in a ceramic material, which forms a hard outer shell on the mold. Next, the wax is removed and hot, liquid metal or alloy is poured into the ceramic shell. When the metal solidifies and cools, it becomes a cast metal product encased in a hard ceramic coating.

The next step is to remove that coating, typically with one of five commonly-used methods.

IMPACT REMOVAL

Impact removal is the oldest and simplest way to remove a shell. It is done manually: a person uses a tool — typically some form of a hammer — to break the shell material.

This method offers the lowest cost of entry and is adaptable to multiple part configurations. However, it is labor-intensive and often results in a level of removal that is less than acceptable. Sometimes even repeated chipping does not remove every shell fragment, so the casting must be subjected to additional removal steps with increasingly smaller chisels and picks. This is tiring for the person wielding the hammer and increases the potential for damage to the casting.

SHAKING

The shaking, or agitation, method involves placing the castings in a vessel that is vigorously shaken, causing the shell material to fracture and break off. These vessels typically use vibrating tables or some sort of tumbling mechanism.

Advantages of the shaking process include the flexibility to handle a variety of part sizes and configurations, and a minimal need for fixturing. In some cases, though, (e.g. complex parts) the shell may not be completely removed.

Also, shaking that is violent enough to fracture a shell may do damage to the castings. The entry cost of such equipment is moderate, but like any machinery it requires some capital investment and a degree of maintenance. Should it break down at any point, downtime and repairs will add to the expense.

SHOT BLASTING

In the shot blasting process, abrasive media is directed at the shell at high speed. This effectively removes shell material, even in hard-to-reach areas when deflective removal is used. Like the impact and shaking methods, it easily accommodates various part sizes and tree shapes, and requires no fixturing.

CHEMICAL

A fourth method of shell removal is chemical cleaning. Here, the castings are soaked in a caustic bath that dissolves the shell material. This typically removes the material quite consistently, without fixturing, and offers the same flexibility as the first three methods. Unlike those methods, however, it raises workplace safety and environmental concerns. Careful storage and handling is required of the hazardous chemicals involved, and proper disposal of the resulting effluent is essential.

WATER JETTING

Water jetting is an increasingly popular method that blasts the ceramic shell with a powerful stream of pressurized water. A pump unit supplies the water, which can be directed manually or with varying degrees of automation. The process is clean and repeatable. In most instances it does no damage to the castings inside the shells, even those with sharp edges or thin walls. Its advantages, disadvantages and costs vary with the water pressure involved and the level of automation.

Choosing a water jetting solution

When evaluating the various water jet options for removing ceramic shells, a number of factors must be considered:

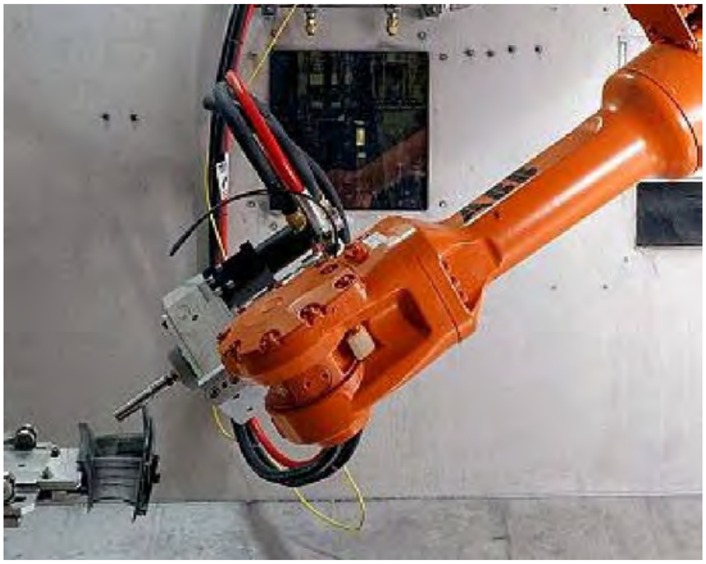
Production volume - How many shells per day (or shift) must be removed?

Removal rate - How much time is required per part?

Fixturing requirements - What is the best way to hold the part in place?

Automation - Are the castings of similar size? Automation is easier when they are. Also, do volumes justify the cost of automation? Higher levels of automation often require greater initial investment. And maintenance time and expense should not be overlooked.

Part complexity - Will nozzle rotation and the spinning of the tree expose enough surface for 100 percent shell removal? Complex shapes may require additional water jet stations.



PRESSURE AND FLOW

The combination of the pressure and flow of the water jets is key in achieving acceptable rates of shell removal. Following are the three categories of water jet removal systems:

Very Low-Pressure water jetting (2,000 psi to 5,000 psi, at 2-5 gallons per minute) is usually performed by an operator with a hand lance. This gives the user considerable flexibility in terms of the shell size and complexity. While the cost of entry is low, manual water jetting at these pressures is typically a slow process. And low-pressure water jets do not break hard shells as easily as high-pressure water jets.

At **Low-to-Medium-Pressure** (10,000 psi to 20,000 psi, at 5-30 gpm), users get the same flexibility with much greater efficiency. This is especially true with automation, which has the additional advantage of reducing operator fatigue. Medium-to-high pressures are best for less-detailed trees with more shell material. A typical set-up has the part fixtured on a turntable in a steel cabinet, targeted by a nozzle mounted on a lance. The cabinet keeps the debris and the water contained while dampening the noise level.

Ultra-High-Pressure, **or UHP** (30,000 to 40,000 psi, at 3-10 gpm) water jetting is a relatively recent option for removing ceramic shells. It is particularly efficient for castings that have small passages or detailed areas that require probing. UHP waterjets are very powerful at a close standoff from the shell surface, but their power dissipates quickly once the jet hits the shell. UHP removal typically requires more time per part than lower pressures. Large castings may present a challenge. One additional advantage that UHP water jetting offers is that it is capable of cutting the wire in reinforced shells.

AUTOMATION

No matter the pressure being utilized, the decision on how to apply the water is an important one. Fixturing the part and using a hand lance is a good, low-cost option. But as volumes increase, rotating nozzles directed at trees mounted on a turntable offer increased productivity at higher (but moderate) cost. Robotic water jets offer the greatest production rates and flexibility. These are programmed to move a rotating nozzle all around the part, spending more time on areas that require it.

WATER HANDLING

Once the decisions on material handling and the pressure and flow of the waterjet is selected, consideration should be given to handling all the water that the process will be using. The most environmentally responsible approach — and usually the most economical — is to recycle the water and reuse it. Here again there are a number of factors involved:

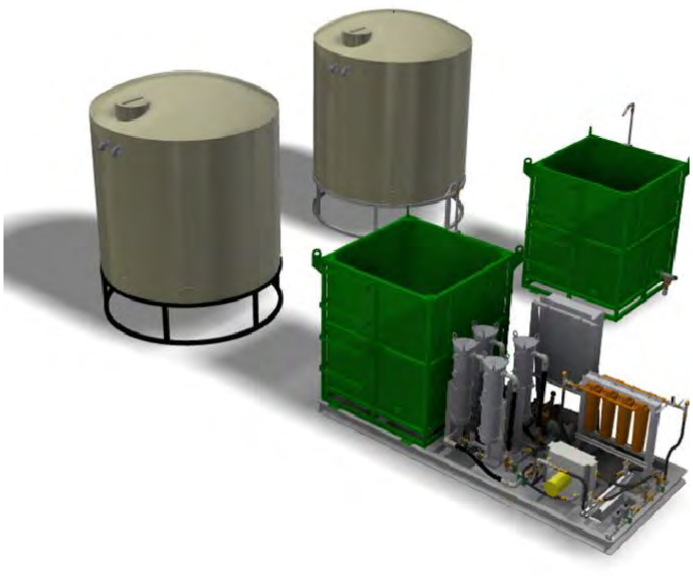
Volume - The amount of water used will depend on the pump's pressure and flow and the shell removal rate.

Shell removal – Not all shell material will be dissolved into small particles. How will the system handle the larger sections of shall that will fracture off during the removal process?

Filtration - The small particles of ceramic debris must be reclaimed for proper disposal before recycling the water.

Pump type - The level of filtration necessary depends to some extent on the operating pressure of the pump. A UHP pump, for example, is far more sensitive to particulates than a 10,000 psi pump.

Water chemistry - The filtration process produces changes in the chemistry of the water, so periodic testing should be conducted to confirm that the recycled water remains suitable for water jetting. This typically means monitoring the PH of the water and adjusting accordingly.



CONCLUSION

Ceramic shell removal is a crucial step in the investment casting process, with major implications for quality as well as productivity. The five well-established methods all have strengths and weaknesses that must be matched to one's specific application needs. Water jetting is not the simplest (or most economical) way to remove shells, but it is highly effective, will not damage castings, and can be automated in a variety of ways to maximize productivity.

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INVESTMENT CASTING INSTITUTE

Industry 4.0 and the Foundry of Tomorrow

Imed Bourega
Shell-O-Matic

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 6

Title: Industry 4.0 and the Foundry of Tomorrow

Abstract:

Digital transformation is the process of using digital technologies to create new or modify existing business processes, culture, organization and customer experiences to meet changing business and market requirements. One important note about digital transformation is that it's enabled by technology; the business improvement comes from how that technology is enabling people or a workforce to create more value than they ever could before. Although digital technologies have existed for a long time, they have primarily been used to help manufacturers automate and optimize their core production processes. What is different today is that new digital technologies are enabling the same sort of improvements across the enterprise in other operational areas like reliability, safety, energy consumption, and many more.

When we talk about Industry 4.0 and digital transformation, they mean different things to different people. While they are different, very often people use these terms interchangeably, along with other buzz words like: Industrial Internet of Things (IIOT), Artificial Intelligence (AI), Machine Learning (ML).

The purpose of this paper is to demystify Industry 4.0 and digital transformation and bring more clarity on the meaning of each of them. This paper will also clarify some preconceived ideas about digital transformation which prevent some manufacturers from adopting new technologies and addresses the main reasons why they fail while implementing their digital transformation strategy. This section addresses the point of what is digital transformation.

Then the paper addresses the point of why it's important and vital to digitally transform the companies now and the benefits they will get by adopting digital transformation in their operations. Finally, the presentation addresses the how such implementation can be conducted for both big and small organizations.

Presenter: Imed Bourega

President & CEO

Shell-O-Matic

INVESTMENT CASTING INSTITUTE

Intercoat Drying & Shell Characteristics for Investment Casting Industry

N. Vigneswaran
SAN Precision Alloys Private Limited

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 7

Intercoat Drying and Shell Characteristics for Investment Casting Industry

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Abstract:

An essential phase in the process of creating an investment casting shell is Intercoat drying. It has been demonstrated that the amount of water removed after each layer of the shell has a significant impact on the mould's qualities. Unfortunately, we are unsure of the precise amount of water that has to be evacuated. Additionally, we lack a trustworthy way to link the measurement of dryness to the quantity of water still present in the mould.

Intercoat dry time can have an influence on casting quality and shell throughput. Under-drying can cause dewax cracking or metal leakage at the casting, whilst over-drying can significantly reduce the output of the shell chamber. The ideal dry time will provide the best moulds in the shortest period of time.

On how much water has to be evaporated during drying, there is significant debate. The drying process must go on for at least long enough for the binder to begin to gel; otherwise, the coating will flake off when it is re-dipped.

In order to determine the link between the degree of dryness, mould characteristics, and the dryness measuring technique, this study was undertaken.

Introduction:

We are facing in-house rejection percentage 15% initially for Seal plate casting which is using in oil flow line in engine of 4 wheeler. The oil passage area is as cast and required the flatness is +/- 0.30mm. Due to insufficient dryness time of the shell, we are facing the shell drying crack, extra metal, inclusions and etc., So that we unable to meet the productivity. Here, we set the Slurry/stucco mixing ratio and its related parameter like temperature, humidity and viscosity. Based on the trials, we reduce the rejection percentage from 15% to 4%. But, till the study is going to eliminate the rejection.

Trials:

Based on the previous trials. We increase the number of coatings. Earlier, we take 8 coatings and set the dryness time for 8-10 hours. Now we take 11 coatings (Sl.No. 3,4&11) and set the dryness time as per the below table

Sl.No.	Slurry	Stucco	Dryness Time
1	Primary Coating	Zircon Sand	08-10 Hrs.
2	Secondary Coating	50/80	12-14 Hrs.
3	**Seal Dip**	**16/30**	**08-10 Hrs.**
4	**Secondary Coating**	**50/80**	**12-14 Hrs.**
5	Back-up Coating	30/80	08-10 Hrs.
6	Back-up Coating	30/80	08-10 Hrs.
7	Back-up Coating	16/30	08-10 Hrs.
8	Back-up Coating	30/80	08-10 Hrs.
9	Back-up Coating	16/30	08-10 Hrs.
10	Back-up Coating	16/30	08-10 Hrs.
11	**Seal Dip**		**12-14 Hrs.**

Drying Study:

Temperature is one way to track the development of mould drying. This method makes use of the mould temperature's response to evaporative cooling (latent heat of vaporisation). There is a lot of water at the mold's surface during the early stages of drying. This surface water will cool through evaporation, bringing the temperature of the mould closer to that of a moist bulb. It gets harder and harder for the remaining water to go to the surface of the mould as drying progresses and water volume decreases. The temperature of the mould will start to rise when the speed of water transmission to the surface restricts the rate of evaporation. There is almost no water left in the mould when the temperature reaches the dry bulb temperature.
Mould temperature drying curve / graph will be provided in the PPT.

Monitoring the progress of drying can also be done by measuring water weight loss. The drying rate can be calculated by graphing the weight of the mould over time. In Figure 6, Moulds that dry uniformly can be monitored using this technique for drying progress. Unfortunately, the majority of moulds do not dry evenly.

By measuring the internal humidity of the mould, the degree of dryness can also be monitored. This technique makes use of a unique digital sensor that is incorporated into the wax pattern. The sensor is shielded by a lid that allows vapour to contact one end of the sensor while keeping the other end dry and breathable.
Here, water loss rate graph and temperature Vs humidity graph will be add in the PPT

Many anecdotal reports suggest that binder rewetting is another factor contributing to the increased strength. According to the idea, the degree of strength enhancement is directly connected to the quantity of rewetting that takes place between layers, which each deposit extra binder into the spaces left by the preceding layers.

The pores must be open and free of water for the binder to wet earlier shell layers. Therefore, pore space accessible for rewetting and the binder's capacity to wet these open pores are directly related to strength improvement.

Conclusion:

Based on the trials, the seal plate internal rejection is reduced from 15% to 4.%

It is found that the seal plate casting internal rejection due to combined effect defects caused by number of coating and improper dryness

All the relevant graphs will incorporate in the PPT

INVESTMENT CASTING INSTITUTE

Foundry 4.0 – Shell Room Experience with Slurry Track Inline Viscosity Monitoring and Control System

Dr. Sunil Kumar & Dr. Joe Goodbread
Rheonics GmbH

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper No. 8

Foundry 4.0 – Shell Room Experience with SlurryTrack Inline Viscosity Monitoring and Control System

Sunil Kumar PhD, CEO Rheonics GmbH; Joe Goodbread PhD,CTO, Rheonics GmbH

Purpose

Last year we presented an overview of our Rheonics sensors, emphasizing the advantages and benefits to be had by automating casting slurry viscosity and density. At that time, we were a fairly new presence in the world of investment casting, and then (as now) on a steep learning curve. Today, we would like to share experience that some of our early adopters have gathered over the past couple of years, with the goal of making our and our customers' learning available in the interest of advancing automated slurry monitoring and control in the investment casting community as a whole.

We will start off with a review of the importance of viscosity and density control with a view toward shell room automation, answering questions like:

- Why are slurry viscosity and density important in shell building?
- An evaluation of traditional methods for controlling slurry viscosity and density
- Factors affecting a viscosity/density measuring device selection for slurry application

Viscosity and density: Importance in shell building

Viscosity is a measure of a fluid's resistance to flow. Viscosity of slurry has a profound effect on the quality of each layer deposited in building the shell. By influencing the rate at which slurry runs off a pattern that has dipped and removed from the drum, it determines the ultimate thickness of the layer. If the viscosity is too low, the slurry will run off too quickly and result in a thin, excessively fragile shell layer. If too thick, the layer will also be too thick, and may dry incompletely and unevenly.

Tighter control of slurry viscosity has been found to contribute to the ease and quality of shell building, as well as the quality of the finished cast goods.
Several literature and studies to investigate the effect of controllable shell building process variables on the shell properties cited viscosity as an important input variable.

Density is also an important parameter for characterizing slurry. Density is a measure of the total solids content of the slurry, and may not be directly related to viscosity. Over the past year, users have shown an increasing interest in density monitoring in addition to viscosity. The SRD offers density measurement and viscosity monitoring in one compact sensor.

Shell properties affected by viscosity and density of the slurry:

Layer & final thickness
Surface finish

Permeability
Strength
Edge coverage
Edge strength
Bending strength
Thermal characteristics

Requirements for a viscosity/density monitoring device from the casters' perspective

Whatever means are used to measure slurry viscosity, the caster should not need to be a measurement specialist. A good, reliable and unobtrusive measurement system provides a trusted tool, rather than an added burden to the caster's craft.

The traditional method of measuring slurry viscosity is the Zahn cup, a kind of efflux cup, that measures – or rather estimates – the viscosity of a slurry sample taken from the drum. The operator dips the cup in the slurry, closing the hole at the bottom of the cup with a finger. They then start a stopwatch, while simultaneously opening the hole. The stopwatch is stopped when the last drop leaves the cup. The number of seconds from full to empty depends on the viscosity.

A number of subjective factors limit the precision – the repeatability – and therefore the reliability of the measurement. These include:

- The operator's judgement of when the cup is empty – is it the last drop to leave the cup? Or when the stream of slurry breaks up into drops? Even though a particular operator's measurements may be repeatable, do different operators' measurements agree with one another?
- How clean is the cup? Repeatability of the measurements requires that the cup's volume has not been changed nor has the hole been narrowed by deposits of dried slurry. Repeatable and reliable measurements require a completely clean, undamaged cup, free of all deposits and residues.
- What is the temperature of the material in the cup? Viscosity is notoriously dependent on the temperature of the fluid, and can vary greatly with even small temperature variations. A reliable and repeatable measurement requires accurate measurement of the fluid's temperature, which is impossible with a typical Zahn cup.

In addition to these key factors, human nature also plays a role in slurry viscosity and density measurement. The measurements require interrupting the workflow to pull a sample from the drum. The measurement is messy and somewhat unpleasant. Operators may delay or even neglect cup measurements for this reason. And because other operations demand their attention, they may not clean the cup as thoroughly as is necessary for the next operator to make accurate measurements.

Despite its limitations, Zahn cup viscosity measurements have become a *de facto* viscosity measurement in investment casting, as in many other industries. Users often ask us if SlurryTrack viscosity measurements, expressed in centipoises or mPaS (millipascal seconds), can be converted to cup seconds in order to provide continuity with their current measurement methods.

The SlurryTrack software allows the user to build their own correlations between cup seconds and centipoise readings. As in nearly all applications that measure viscosity of non-Newtonian fluids, there is no universal conversion factor or formula for direct conversion. However, users report that for each formulation of a particular material, a workable conversion formula can be found. But because the conversion is dependent on the composition of the fluid, each user must perform their own correlation based on their own cup measurements.

Laboratory measurements may be more accurate but come with their own problems. In addition to the messiness of drawing samples, they introduce a sizable delay between sampling and reporting of results. That means that any corrective action will be based on a *previous* condition of the slurry – typically hours, or even days ago – and not on its current condition. This makes using lab results for slurry consistency correction an uncertain and risky business.

On top of these factors, slurry is a “living” fluid – its condition is based not only on its composition and its temperature, but on its flow history. Slurry in the drum – the slurry that will ultimately coat the pattern – is in constant motion. Slurry that is drawn from the tank is stationary. It will flow differently through a hole in the Zahn cup, or around the rotor of a lab viscometer, differently from the way it flows in the drum. In the case of lab measurements, the solids in the sample may begin to settle, making the sample non-uniform.

An ideal viscosity and density monitoring system should be:

- Repeatable – measurements made today on the same slurry composition should match those made yesterday or tomorrow.
- Sensitive and precise – differences in slurry behavior that are relevant to its performance in shell building should be clearly and reproducibly registered by the monitoring system.
- Capable of measuring in the drum while patterns are being coated – in-drum measurement allows for taking immediate corrective action as slurry consistency drifts out of its specified limits. Sampling interrupts the workflow, while yielding imprecise measurements of questionable usefulness.
- Robust enough for in-drum measurements – Delicate, easily damaged sensors are unusable in the slurry drum. A suitable sensor must not only survive possible rough handling and abrasive slurries, but also thorough cleaning and removal of tenacious deposits of accidently dried-on slurry.
- Capable of taking continuous measurements, at a rate that is useful to the operator, or necessary for automated consistency control.
- Should not require calibration – its accuracy and repeatability should remain unchanged over years of operation.
- Should be compatible with factory and enterprise data systems and models – should have interface and data format that can be read by PC, PLC, or any other device used by the caster to collect and analyze process data, and to give control commands to process systems.
- And perhaps most important, should be “transparent” to the operator – it should not interfere with the operator’s workflow, but should alert them to any irregularities that develop in slurry consistency.

Rheonics SRV/SRD and **SlurryTrack technology** offer a simple and efficient bridge to bring slurry management up to the modern standards that prevail in today's highly automated shell rooms. It is based on small, very robust density and viscosity sensors, coupled with an advanced, industry 4.0-ready data analysis and control system.

Details of the system's design and implementation have been discussed elsewhere, so only a brief summary is necessary here.

The system consists of a sensor and the SlurryTrack analysis and control system. The sensor is less than six inches long, and weighs about a half pound. Nevertheless, it can withstand the rigors of continuous operation in the most aggressive slurries, as well as cleaning procedures for removing dried-on residues, without ever requiring recalibration.

The sensor's compact construction has proven a great advantage for in-drum installations. Operators usually make use of the protection cage and long insertion stem that are available with the system. The cage protects the sensing element from damage through accidental collision with the drum walls or other objects, while the stem facilitates rapid and easy removal of the sensor for periodic cleaning and storage if the drum is taken out of service for any reason. In addition, a quick-release mounting system is available to facilitate easy removal and repeatable placement in the drum, if the probe needs to be removed for cleaning, or for drum maintenance.

Figure 1. Rheonics SRV viscosity sensor

Figure 2: Rheonics SRD density and viscosity sensor

Moving on to the analysis and control unit, SlurryTrack electronics is delivered in a stainless steel cabinet with DIN-rail mounted components and an industrial PC with touch-screen control. In addition to providing an intuitive operator interface for data collection and control settings, the SlurryTrack cabinet has connections for a wide variety of interfaces, including Modbus, Ethernet, 4-20mA channels, HART, USB, and Bluetooth. This allows SlurryTrack to work and play well with enterprise data systems, making it particularly useful for correlating measured slurry consistency with shell and casting quality measures, over long time periods. The rich data collection and analysis opportunities it offers allow detection of potential problems before they have a significant impact on shell and casting quality and yield.

Now we move on to how to give viscosity and density monitoring a place in the shell room, in general, and some strategies for implementing it in practice. This will take us into points such as:

- Setting up a viscosity and density monitoring system, including installation
- Strategies for monitoring viscosity, starting with simple graphing of viscosity and density data, all the way toward setting up slurry profiles, alarms, and preparing the way for full process automation
- Implementing automatic control of slurry properties
- Dealing with the tough realities of the shell room - cleaning and maintenance of viscosity and density sensors in an abrasive and adherent world
- The possibilities of process optimization presented by automatic monitoring and control.
- Future music - the role of a learning community for taking shell room automation from a buzzword to an everyday reality.

Setting up viscosity and density monitoring

The hardware store: making room for the viscosity/density sensor in the slurry tank

Installing a viscosity and density measuring system in the slurry drum requires a bit of planning. Some considerations are:

- Planning phase:
  - Do you need viscosity and density measurements, or is viscosity sufficient?
  - Will you be monitoring more than one drum in the same shell room?
- Where will you install it on the drum?
- Where will you locate the monitoring and control cabinet?
- How will you connect the system to your enterprise data network?

Before you order a system, you will need to decide if you need both density and viscosity measurement, or if viscosity alone will do. Although viscosity and density are both important for slurry drum monitoring, some users find that viscosity is sufficient for their needs. Viscosity monitoring alone has several advantages, the most important being that Rheonics' SRV sensor can detect buildup of deposits on its sensing element and can alert the operator that cleaning is necessary. Density sensors generally cannot distinguish between deposits on the sensor and increases in measured density, since both load the sensor with additional mass. So for highly deposit-prone, sticky slurries, the SRV, which measures only viscosity, may be a better choice. Before deciding on a sensor, it makes sense to ask yourself what you will use the measurements for. If the measured values are intended to trigger either a manual or automatic correction of the slurry, will density or viscosity be the deciding factor? This can help guide your initial sensor selection.

How many sensors will you be operating in each shell room? If the answer is more than one, it will pay to consider getting a system with multi-station monitoring that can service and monitor several slurry drums at once. Rheonics provides SlurryTrack systems with up to 12 stations, so that only one cabinet is necessary to monitor up to 12 stations simultaneously. A single industrial PC services all of the sensors, and produces operator-selected display and, when installed, control modes for each station.

Setting up the sensor in the slurry drum

Users report that it is both best practice and most convenient to install the sensor near the inner wall of the slurry drum. There are two reasons for this. First, it is advantageous to have as large a flow velocity across the sensor as is possible. Since slurry is a shear rate-sensitive fluid – its apparent viscosity varies strongly with how strongly it is being sheared – having a higher flow rate has been found to give the most stable and reproducible readings.

Therefore, we now give narrower guidelines for sensor installation. Because the sensors may be installed in any position, we previously left it up to the user to figure out how best to install it. But we found that users asked for more guidance, or else made mounting decisions that were less than optimal for the particular situation. Therefore, we currently make recommendations for things like minimal distance of the probe from the tank wall, immersion depth, and in the case of the SRD, the orientation of the sensor with respect to the flow direction of the slurry in the tank.

Users have also pointed out that the slurry density and viscosity values vary with depth of the probe in the tank. Since the slurry level drops as shells are built, there is no "perfect" position for the probe. However, the variation of readings with depth is much smaller than the repeatability errors of cup measurements, and lies within the tolerance limit of most slurries. It is therefore recommended to place the probe at a depth that will ensure that is always completely immersed in slurry, no matter what the operating level of slurry in the tank.

The SRV and SRD are available with a tank mount adaptor, that encloses the sensitive part of the probe in a strong stainless steel cage, and provides a ¾ NPT pipe as a mounting stem that enables submerging the sensor to the proper depth in the slurry drum. The immersion depth should be sufficient that the sensor is never above the fluid surface during the course of operation, and it should be high enough in the drum so that it doesn't contact the bottom.

A quick-release mounting system is available that facilitates easy removal of the probe from the drum when cleaning is necessary, when slurry is being replaced, or when other maintenance is being performed on the tank. In all cases, there must be means for washing down the probe when it is removed from the slurry. If slurry is allowed to dry on the probe, it may form a hard, tenacious coating that is difficult to remove, possibly calling for chemical removal. Mechanical removal of long-dried slurry on the probe risks damaging its sensing element. There should always be a bucket of clean water available near the drum in which to immerse the sensor, in case it needs to be removed, as a short-term alternative to a washdown. The arrangement of the sensor in a slurry tank is shown schematically in Fig. 3.

Figure 3: SRV/SRD in slurry tank

Monitoring: **Connect and go!**

Once the probe is installed in the tank, it is connected to the SlurryTrack cabinet by means of a sensor cable. In the event that the cabinet needs to be installed outside the shell room, cable lengths of up to 500 meters can be used without affecting the measurements.
Then turn it on and it's ready to go! The instruction manual will show the operator how to get a first display of the viscosity – and in the case of the SRD – the density of the slurry.

In a next step, the installer hooks up whatever interfaces are needed to connect the SlurryTrack to an enterprise data network. The installation and operating manual supplies all the necessary information, backed up by a competent support team that includes interfacing and networking specialists.

What to expect from monitoring software

Looking at a display of the raw data as it comes from the sensor may be confusing. Slurry is not a uniform, homogeneous fluid. Bits of solidified material may be carried along with the material circulating in the drum. All of this adds "noise" to the raw measurement data. But closer inspection of even the raw data shows that there is a baseline value to which the measurements repeatedly return. And the duration and time of the noise glitches are usually much faster than any actual changes in the bulk slurry. Therefore, filtering functions are available that enable the operator to filter out the noise and display only the trend of density and/or viscosity. And it is this filtered measurement value that allows the system to control the slurry properties without, for instance, adding water every time the viscosity measurement twitches "up".

Processes that change the viscosity and density of slurry include temperature changes, evaporation, and removal of material from the drum. These are all relatively slow processes, so low data rates are preferable to fast-responding sensing. We don't want alarms going off every time the slurry is agitated by insertion of a pattern in the drum, but we do want to follow slow changes in the slurry properties to avoid shell defects and rejected cast parts.

Control

Automatic viscosity control is the gold ring that we'd all like to grab. Automatic viscosity control using conventional "grab and measure" monitoring with the Zahn cup is not possible, and laboratory instruments too fragile and fussy for shell room, in-drum service. True automatic slurry consistency control needs a stable, robust sensor that will not change its properties despite exposure to the abrasive,, rough-and-tumble world inside the slurry drum.

The Rheonics SRV and SRD offer the stability needed for reliable automatic slurry viscosity and density control. Backed up by the Rheonics SlurryTrack predictive tracking control system, the tools are finally available to enable automatic slurry monitoring AND control.

In developing the SlurryTrack predictive tracking control system, user feedback has been an essential part of the process. We have learned that slurry increases in viscosity very slowly. Therefore, any control system must take that into account. If the system is being used to control the slurry consistency by dilution, it is important to *never* add so much diluent that viscosity drops below the minimum allowable value. Correction of overdiluted slurry may require reformulation of the entire tank contents.

Preventing over dilution requires a “conservative” controller that does not trigger dilutions on occasional spikes in the sensor readings, but makes use of stored historical data to judge whether and when dilution is called for. And when dilution occurs, it is in small portions, smaller that is usually used for manual correction of tank viscosity. That way, the system can measure the response of the tank to these small additions, and keep the slurry viscosity in a very narrow range, rather than the jumps experienced when large quantities of diluent are added because the latest cup readings show excessive viscosity.

The technology is still taking baby steps. In the last few years we have heard encouraging reports from adopters of our system, leading us to believe that full shell room automation is within reach. But we are all on a learning project, and this will be the subject of the last part of this presentation.

Fig. 4 shows how the SlurryTrack can be connected to provide viscosity or density control using a valve to dose diluents or other additives.

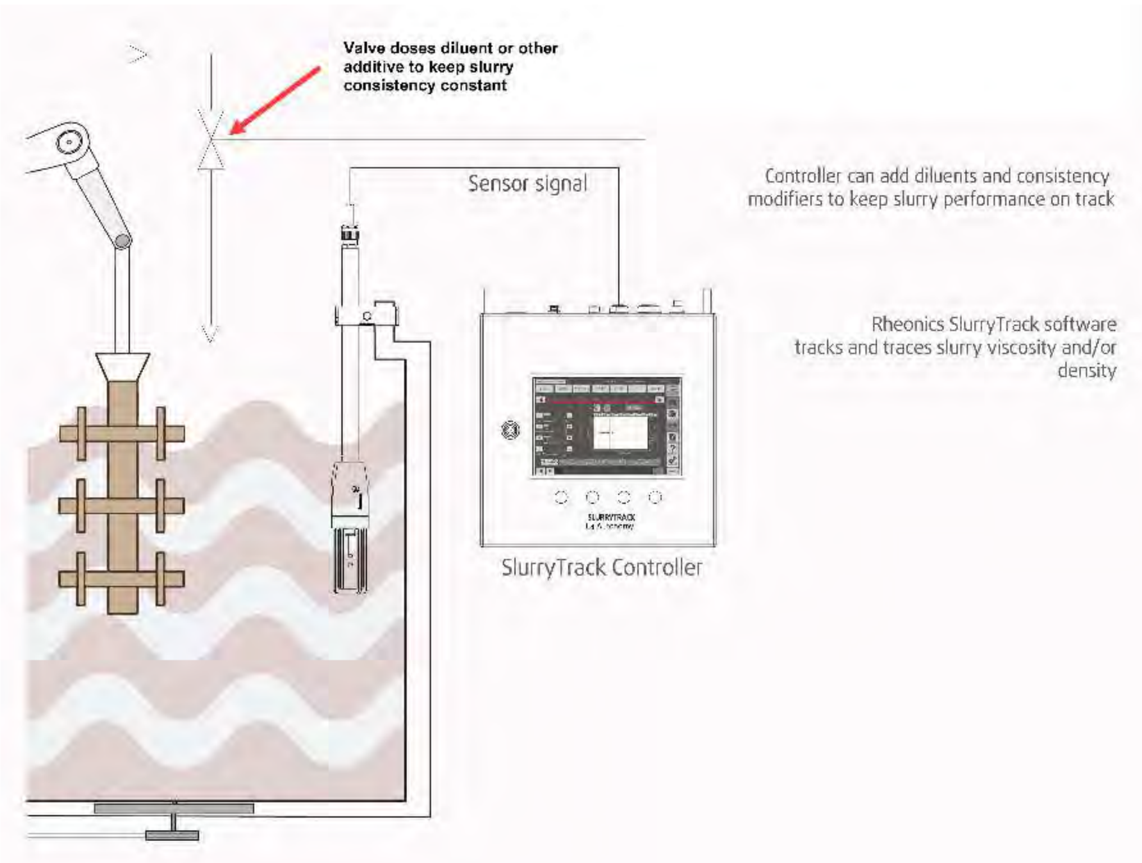

Figure 4: Slurry consistency control with SlurryTrack

Clean sensors in a challenging environment

The purpose of shell-building slurries is to adhere to and form a uniform coating on wax patterns, a difficult surface for *anything* to stick to. But a wax pattern only needs to survive one trip through the slurry tank - it eventually goes to pattern heaven when it makes room for the molten metal that is the point of the whole operation. A viscosity and density sensor generally has a surface more conducive to slurry adhesion than the wax of the pattern, and therein lies one of the biggest challenges to in-drum viscosity monitoring.

Detecting deposits on the sensor probe, and removing these deposits in an in-line process, has been one of the biggest challenges of implementing in-drum slurry monitoring. There are three main tasks to facing this challenge, which we will discuss individually:

1. Detecting and removing deposits
2. Detecting effects of abrasion on the long-term survival and accuracy of the sensor.

Deposits on our sensors has been an important and recurring concern. Many of the sensors we produce are used in coating processes, from printing to painting to battery electrode coating, and of course, shell building. Coating materials must be adherent – it is a central part of their function. We tried to build a sensor that never needed cleaning, but the non-stick coatings we tried did not perform well and were insufficiently durable. Therefore our focus changed to making the sensors easy to clean. Their inherently rugged construction and hermetic sealing makes them very resistant to damage by mechanical cleaning methods such as high-pressure washing or simple wiping with a rag. In addition, we have listened to operator feedback and have helped them devise standard operating procedures that become an integral part of their process.

Detecting and removing deposits

The SRV viscosity sensor has a self-checking feature built into the SlurryTrack system. The SRV is based on a resonator that is immersed in the slurry. When the surface of the resonator is clean, its resonance frequency tracks in a predictable way with its viscosity reading. If this relationship changes, it can be detected by the SlurryTrack, and can trigger an alert to the operator that it needs to be cleaned.

Cleaning a sensor that has a buildup of wet slurry is usually just a matter of swishing it in a bucket of clean water, or washing it down with a hose. The more frequently this cleaning cycle is performed, the lower the risk that a strongly adherent deposit will form that needs stronger measures for its removal. To our great surprise, some operators have succeeded in removing hard, tenacious deposits from sensors that have accidently been left to dry while coated with slurry. We feared that the sensors were beyond rescuing, but the users found that even these deposits could be removed without changing the sensors' calibration!

In the event of a strongly adherent deposit that won't come off in a bucket of water, washdown with a high-pressure hose may be sufficient. If for some reason slurry has dried on the probe and cannot be removed by washing it, chemical removal may be necessary. The probe is made entirely of 316L stainless steel and is hermetically sealed, so that it will not be affected by chemicals generally used to remove these deposits from other equipment.

In general, prevention is the best cure. Periodic and frequent washing of the probe is usually sufficient to prevent deposits from forming. Users have reported creative solutions to this task, including using a robot arm to periodically remove the sense and swirl it around in clean water. But any approach to periodic, intermittent cleaning will reward operators with more consistent slurry data, without having to compensate for data drift caused by deposits.

Difficulty of detection of deposition on SRD

All of these measures for coping with deposits are doubly beneficial when used with the SRD density and viscosity sensor. Since the sensor measures density by a decrease in its resonance frequency as increased fluid density loads the sensor with additional mass, it cannot distinguish deposit buildup from increase in density. Therefore, it is essential to clean the SRD at short intervals, and to ensure the cleaning method is sufficient to maintain its density accuracy.

Developing and adopting cleaning methods and strategies is an ongoing learning process to produce the best possible slurry consistency despite the quirks of different slurry compositions. Users tell us that different slurries have very different adhesion properties on the sensor. Some are sticky and require frequent cleaning; others are less adherent, and cleaning intervals of hours, days or even weeks are sufficient to keep getting meaningful and useful data from the system.

Process optimization: benefits of enterprise data collection

Continuous monitoring allows long-term correlation of slurry properties with data on shell integrity and cast parts yield. This is only possible when the monitoring system is more stable than the shell building process itself – the more stable the system, the smaller the changes it can detect in slurry consistency. If the variation of the sensors' response is larger than the changes in slurry consistency, you wind up monitoring the sensor rather than the slurry, which is kind of beside the point.

Long-term measurements of slurry consistency trends and their correlation with overall process efficiency and yield is only possible with automatic monitoring and logging systems, such as the SlurryTrack and its associated sensors. We foresee a time when this and similar systems will enable optimization not only of slurry stability, but also slurry formulations, since it will then be possible to "tweak" and maintain slurry composition with much finer granularity than is possible with Zahn cups or with periodic grab-and-lab slurry tests. And this brings us to the final part of this presentation -- the role of community in the future of shell room automation.

Future prospects

The purpose of organizations like ICI is not only to provide a forum for meeting and greeting our fellow investment casting people - it also functions as an essential vehicle for community learning. ICI actualizes the potential in the investment casting community as a place to share experience that raises the general standard of the industry, from theory through daily practice. The better we do as a community, the better the chances for success of its individual members.

It is in that spirit that we came here this year, knowing that what we consider a great technology can only succeed if it works to ease the job of running a casting operation, and improving the value of the industry’s products and processes in the world marketplace.

We believe in the potential of our systems to improve both the efficiency and quality of investment casting, but we need your help in making that potential an everyday reality. We'd like to thank all of you who have patiently worked with us getting these systems running in real, productive shell-building operations, and who have generously shared their experience and data with us so we can together develop solutions that really work for everyday production. What we hope we offer in return is to free the shell room artisans to focus on building the best shells possible, by relieving them of the complexities of slurry measurements and stabilization.

Acknowledgments

We would like to thank users of the SlurryTrack for very useful feedback on their experience with the sensors and system. Particular thanks to Mark Christensen from PCC Structurals for feedback on this presentation, and for helping us understand some of the basic issues affecting performance of these systems from an operator’s perspective.

INVESTMENT CASTING INSTITUTE

Improved Process & Material Properties in Air Casting Applications by Means of Vacuum CAP (VAP) Furnace Process

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70TH TECHNICAL CONFERENCE & EXPO 2023

Paper No. 9

IMPROVED PROCESS AND MATERIAL PROPERTIES IN AIR CASTING APPLICATIONS BY MEANS OF VACUUM CAP (VCAP) FURNACE PROCESS

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1. Abstract

Vacuum Cap (VCAP) furnace technology combines air melting and vacuum refining into a hybrid process that produces many metallurgical advantages when compared to traditional air melting technologies. Air melting has limitations with regard to the purity of the alloy (low vapor pressure tramp elements), tight composition control, and other metallurgical issues like gas content (oxygen, nitrogen, and hydrogen levels) and high carbon content.
In cases where the full-vacuum melting process is not required, VCAP furnaces take advantage of efficient charging and melting in air, and then a vacuum cap is applied for improved refining of ferrous and non-ferrous metals. This also reduces the scatter in product properties, ultimately resulting in less rejections.

Keywords: VCAP, air melting, vacuum melting, vacuum induction degassing, deoxidation, decarburization, tramp elements.

2. Introduction

Air induction melting technology is a very common and extensive manufacturing method used all over the world, which enables producing complex castings on many different types of alloys.

Performance requirements on alloys are becoming more stringent for end users in industries such as aerospace, medical, power generation, oil and gas, specialty automotive and trucks. These requirements include few if any defects and better mechanical properties. However, these properties are difficult to attain using standard air-melting techniques. [1]

These are the main challenges of the air melting technologies:

- They can suffer from limited control of alloy composition cleanliness.
- Oxygen and nitrogen level heat to heat variability.
- Current practice to decrease gas content is to add virgin material, because deoxidation with only aluminium could result in non-metallic inclusions.
- Low vapor pressure tramp elements like Pb, Bi, Zn, etc. can only be reduced via dilution.
- Carbon reduction is a metallurgical challenge in air melt.

In this point, VCAP technology becomes a great solution to face all these challenges listed above, because of the advantages unique to the vacuum induction melting process, such as excellent control over the entire alloy chemistry, not only the desired alloy composition but also the beneficial trace elements and harmful impurities. Additionally, the reproducibility of precise composition control from heat-to-heat is exceptional and results in a remarkable consistency of material properties at high levels.

Figure 1. 80kg (left) and 1.5t (right) VCAP furnaces.

VCAP technology, shown in Figure 1, is a hybrid process that combines the techniques from air melting and vacuum induction melting ones (VIM). It is essentially an air melting furnace that includes a cap that can be placed on the top of the induction melting coil enabling vacuum degassing cycles once the alloy is fully melted in air.

Figure 2. Sketch of VCAP technology as a mixture of air melting and vacuum melting (VIM) technologies

Figure 2 explains the basics about VCAP technology showing on the left hand-side an air melting furnace, on the right-hand side a vacuum induction melting furnace, and finally, the VCAP furnace in the middle, shown as a **hybrid technology** between the other two technologies. There is an arrow indicating that capital investment, complexity and quality of the material produced increases as you progress from left to right.

Overall, VCAP furnaces offer a powerful combination of precision, purity, and flexibility, making them an ideal choice for producing high-performance alloys and other advanced materials.

3. VCAP main highlights

VCAP technology includes the following main highlights that make it an advantageous option compared to air melting technology:

- It is available in a wide size range from 50kg to 30,000kg, allowing customers to choose furnaces sized for small pour weights or research purposes, and also for large pour weights.
- Vacuum levels ranged from 100mbar to 0.01mbar. Vacuum levels highly depend on the C and O composition and following decarburization reaction.
- Argon partial pressure atmosphere melting also available.
- Argon/nitrogen porous plug systems are available for additional agitation inside the melt and then, promote good mixing, degassing and overall metallurgical reactions.
- Can be used to process almost all metals:
    - It is available to melt and mix of selected raw materials / revert.
    - Ferrous and non-ferrous alloys.
- Some different metallurgical processes may be achieved:
    - Reduction of hydrogen, oxygen and nitrogen (vacuum degassing).
    - Reduction of low vapour pressure tramp elements like Pb, Cd, Bi, Zn.
    - Deoxidation using combination of vacuum and C-O reaction.
    - Decarburization - intensified C-O reaction at low pressure enabling excellent decarburization for extra low carbon levels (improvement of alloy workability/machinability).
    - Desulphurisation (limited) – Use of reducing slags and / or powder injection in air or controlled atmosphere

As a result of that, a **better micro-cleanliness** due to strong carbon deoxidation and smaller residual inclusions, is achieved, and subsequently:

- Increase of the fluidity of the metal, which improves filling of the mold.
- Significant improvement of mechanical properties.
- Improvement of technological characteristics like hot workability, weldability and machinability.
- Significantly reduced scatter in product properties and characteristics, so less rejections.

4. Primary applications

VCAP furnaces offer a compelling option for high-quality foundry applications that require an improvement on air melting and do not require full vacuum melting. VCAP furnaces are available to suit a wide variety of applications in sizes ranging from 50 kg (110 lbs) to 20 tons. Typical applications feature the following materials

- Low and high carbon steels
- Stainless steels
- Cobalt-based alloys
- Tool and die steels
- Nickel-based alloys
- Non-ferrous alloys (like Cu alloys).
- Etc

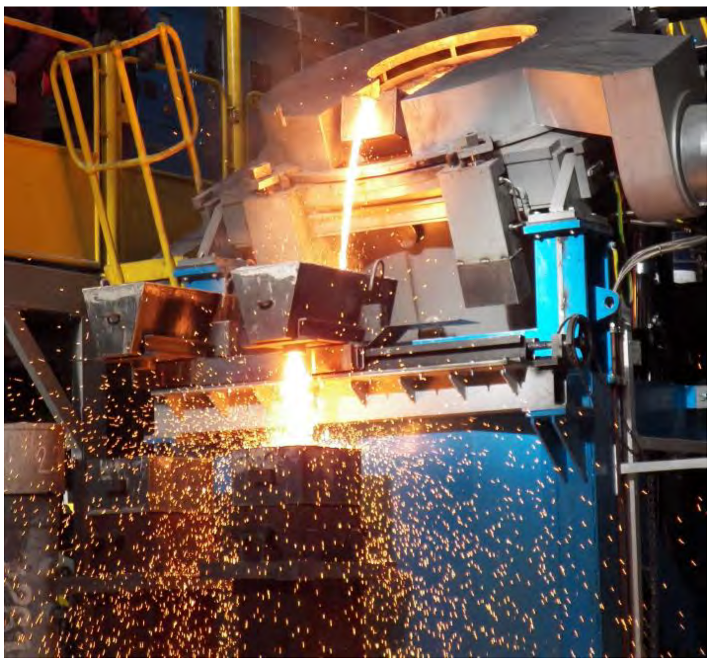

Figure 3. 2,000lb VCAP furnace

5. Process steps

The VCAP furnace is designed for induction melting a solid charge in air or vacuum, with final degassing stage under vacuum. The final pouring of the metal is performed in air or under protective atmosphere of inert gas. Configuration is based on the Inductotherm range of steel shell induction furnaces which are fully adapted by Consarc for vacuum treatment of liquid metal.

The furnace shell is fully sealed for vacuum operation and a sealing flange/apron is provided on top of the unit. Following the air melt operation (or vacuum/inert gas if required), a water-cooled vacuum lid is placed on top of the furnace, either by factory crane, or optional lift/swing pivot arm. The vacuum chamber is connected to a multi-stage mechanical vacuum pumping system which can evacuate the atmosphere above the molten bath.

The induction melting coil is powered from an Inductotherm VIP Power supply with the power and frequency matched for fast melt rates (high productivity), and optimum stirring (metallurgical quality) in the liquid state. The stirring frequency ensures that the alloy is fully homogenized and that fresh liquid metal is cycled to the surface of the bath to aid the degassing procedure.

Once the atmosphere is evacuated, the degassing procedure and intensified CO reaction allows removal of undesirable gases, Hydrogen, Nitrogen, and Oxygen to much lower levels than would be possible in air.

At the end of the degassing sequence, the vacuum lid can be removed and a protection ring is placed around the sealing flange. The furnace is then ready for tilt pouring into the customer's transfer ladle or molds. The pouring process is usually carried out in air, but options for pouring under protective atmosphere are also available.

The following schematic flowchart summarizes the process:

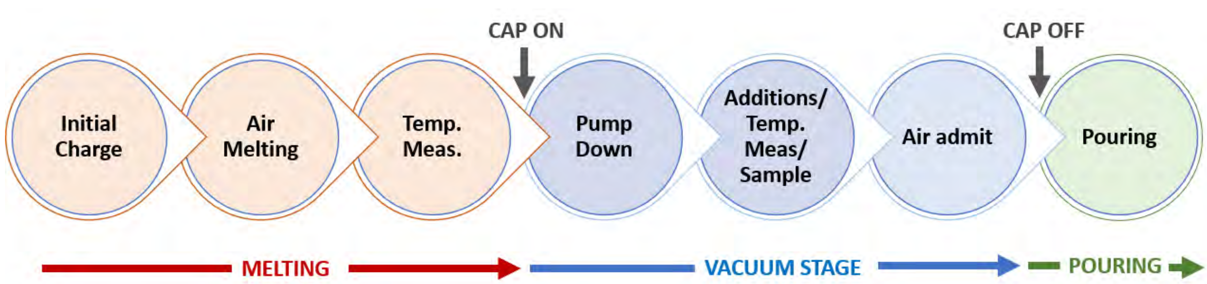

Figure 4. VCAP basic process flowchart.

6. **Case study**

The following case study was performed in July 2022 to demonstrate the advantages of the VCAP technology. [2]

6.1 Introduction

Ecrimesa is an air investment casting Spanish supplier. It started its investment casting production in 1964 in Santander (North Spain) coming from jewellery investment casting.

Figure 5. Picture from Ecrimesa showing pictures from foundry and casting simulation process.

The Tests were conducted at Brno University, on the Consarc 175 lb (80 kg) VCAP furnace.

Figure 6. 175 lb (80 kg) VCAP furnace at Brno University of Technology

The aim of the tests was to utilize VCAP to solve the metallurgical challenges with out of tolerance mechanical tests from their air casting process:

6.2 Description of the tests

- Charge: 175 lb (80 kg).
- Alloy: 34CrMo4 steel. The table shown below includes the typical chemistry of this alloy:

Table I.Average composition of 34CrMo4 steel.

	C	Si	Mn	S	Cr	Mo	Ni	Al
Avg (%)	0.34	0.25	0.70	<0.035	1.110	0.5	30.0	0.4

- *Number of melts*: 3off. 5 shell molds casted on each batch, each mold had x54 parts. The following table explains the details:

Table II.Details from the test melts performed.

Melt number	Air melting	Degassing (min)
1	Yes	No
2	Yes	30
3	Yes	60

- *Mechanical tests*: it is a 3-point ben test performed on specimens taken from the castings. The requirement was the following:
  - Values shall be ≥2.1kN, with only 3 values admitted <2.6kN (but they shall be ≥2.1kN).
  - Average minus x3 std dev shall be ≥2.1kN.

Figure 7. Picture of the 3-point bend testing machine.

6.3 Results of the tests

The results obtained show a clear improvement of the VCAP technology compared to the air melting process. This is a summary of the numerical values obtained:

- *Average*: ~14% higher value
- *Std deviation*: ~ 39% narrower value
- *Max values*: ~ 9% higher values
- *Min values*: ~25% higher values

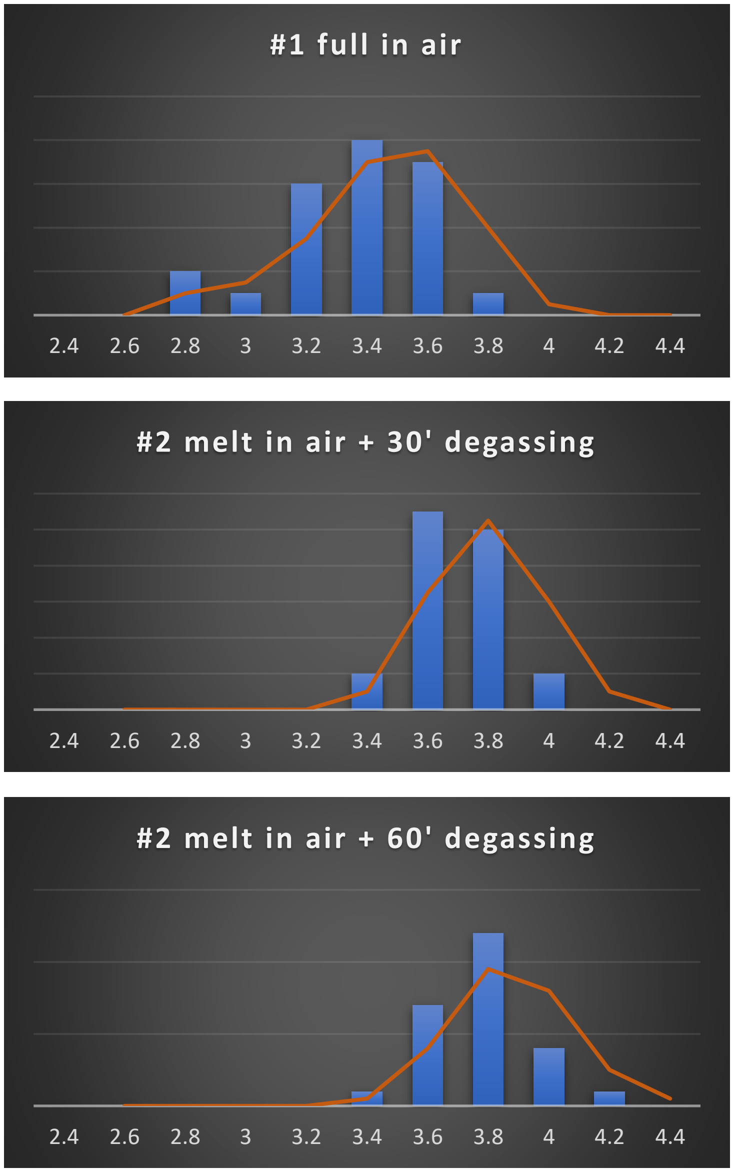

Figure 8. Graphs showing the results of the 3 tests by using the same scale

The numerical results are summarized in the following table:

Table III. Numerical results from the mechanical tests carried out on the 3 test melts.

Sample #	Sample Name	Avg. $F_{failure}$ (kN)	Min. $F_{failure}$ (kN)	Max. $F_{failure}$ (kN)	Std. Dev.
-	Requirements	≥2.6	≥2.1	-	-
1	Air	3.21	2.62	3.74	0.27
2	Air + 30 min degas	3.66	3.25	3.92	0.17
3	Air + 60 min degas	3.67	3.35	4.11	0.17

7. Conclusions

VCAP technology is a hybrid technology between existing air melting and vacuum melting technologies.

It combines the simplicity of air melting process and benefits from vacuum melting, such as reduction of deleterious gases like Hydrogen, Oxygen (by deoxidation) and Nitrogen, low vapour pressure tramp elements like Pb, Cd, Bi, Zn.

Moreover, VCAP process can also perform decarburization and desulphurisation reactions to reduce Carbon and Sulphur respectively.

As a result of the benefits of VCAP technology, foundries can achieve:

- VCAP enables better chemical control of the alloys casted, better micro-cleanliness, clear improvement of mechanical and foundry properties, and an improvement of technological characteristics, like hot workability, weldability and machinability.
- Process improvements and significantly reduction of scatter in product properties and characteristics, and as a result of that, VCAP provides a more consistent casting process, and less rejections on cast parts.

8. References

[1]. Carpenter Technology: outlines how high-tech melting creates high-performance metal alloys.
[2]. Ecrimesa VCAP tests performed at Brno University on Consarc VCAP furnace. *https://ecrimesagroup.com/*

INVESTMENT CASTING INSTITUTE

The Cyclops Ladle

Jorge Arellano
POK

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 10

The cyclops ladle

Jorge D. Okhuysen*, Jorge A. Arellano**

Research and Development, POK Castings

Abstract

In this paper, we will describe how we pursued the benefits of a bottom pour ladle used to cast small molds making modifications in its miniaturization. Talking specifically about the bottom pour ladle, it has moving components and seals in its interior that would make it virtually impossible to be used for small pours, mostly because of the proportion of metal volume to surface area; inducing important heat losses.

As part of pursuing the benefits of a bottom pour ladle used to cast small molds it was decided to make some slight modifications in its miniaturization by taking out the insides and seals of the bottom pour ladle. The process takes place by pouring on its side, this causes a choke in the stream of metal to float the slag. This approach was developed while running a job for a 40-gram Casting of IC 17-4 PH alloy and as a result, high quality surface were obtained, it is expected to keep working on the development of future ladle innovations.

Introduction

For the research, the insides and seals of the bottom pour ladle were removed and it is intended to be used by pouring on its side, which chokes the stream of metal to float the slag, this innovation it was named the "Cyclops Ladle". The testing was made up using a 40-gram casting of IC 17-4 PH alloy in which some shiny black rounded spots that where dispersed throughout the castings in no particular pattern or relation.

These spots were hard to remove even by sandblasting, and they left a negative crater-like dent, rendering the parts to be scrap. We looked at many variables including wax cleanness, shell ceramics, dewaxing, oven firing atmosphere, alloy, the handling of the mold, etc. and all seemed acceptable.

Then we tried using a filter on the mold and noticed that it somewhat helped to eliminate the problem, however now castings had misrun and rounded edges. A mold was cast in the vacuum furnace and the parts came out perfect. By now we knew it was an oxide formation that was what causing the problem. It would have been a good solution to just pour the whole order in the vacuum furnace, but it would have taken a lot of time and at a higher production cost.

Figure 1. Dispersed shiny black rounded spots around the parts

Experimental Design

Looking for a more viable solution, we came up with the “Cyclops” ladle. It is made from fused silica because of its high thermal shock properties and low shrink characteristics. The top of the ladle is a “half lid”.

Figure 2. The cyclops ladle observed from different angles

A hole is made on the upper side of the ladle in the direction of the lid. The ladle is insulated with ceramic fiber and preheated to at least 1700° F. The way that its used, is by filling it with metal to only half of its capacity (40# nominal capacity).

Figure 3. The cyclops ladle observed from an operational view

Then the ladle is tilted back around 45°. By doing this, the slag will stick to the cold wall. Immediately after sticking the slag, the ladle is tilted forward to pour the mold until its completely empty (no heel is left). Pouring is done right on the cup, perhaps even touching it, as this minimizes the exposure to the atmosphere and protects the metal.

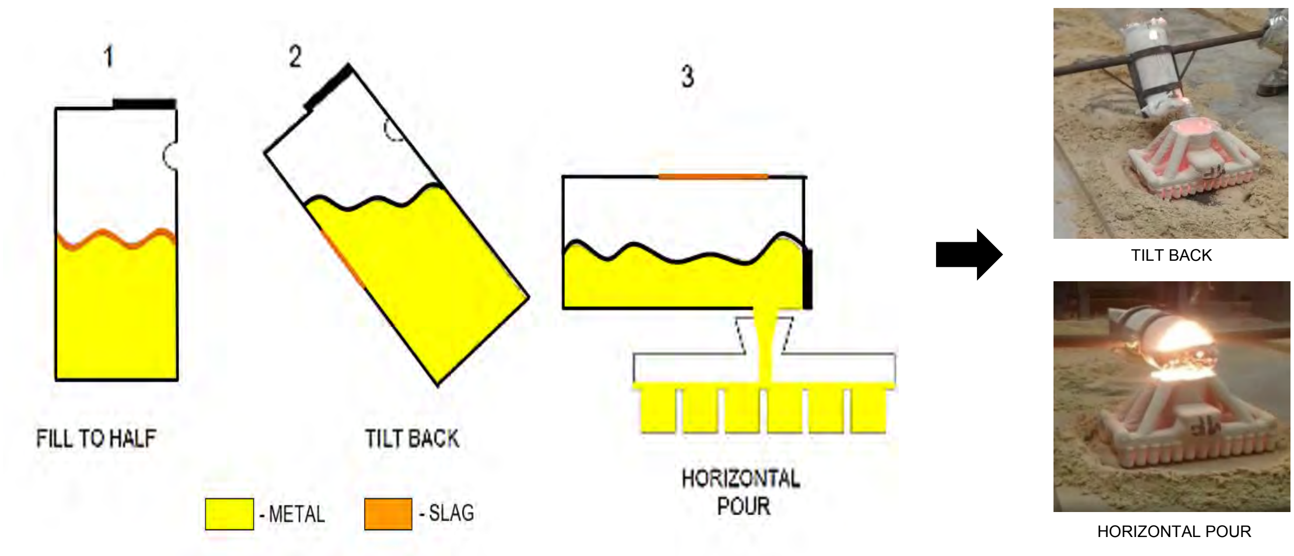

Figure 4. Use principle for Cyclops ladle

(a)

(b)

(c)

(d)

(e)

(f)

Figure 5. Process of pouring metal into a mold using Cyclops ladle

Results and Discussion

This amazingly simple concept made a huge difference for the casting surface, which came out clean with crisp edges. Traditionally, the rate of flow of the pour for a small mold is very fast; some call it “slam pouring”. But rapid pouring is no guarantee that the parts will properly fill.

Figure 6. Castings after shakeout with improved surface

There is a big confrontation that happens between the metal entering the cavity and the air leaving as it is also suddenly expanding and bubbling through the metal. The slow and even flow of metal allows the first metal to enter the cavity, heat the air by radiation immediately; thus, expanding it and forcing the majority of it to leave the mold, well before the majority of the metal is poured.

Pouring slow also allows for the parts to start solidifying, which can then be fed by the last and hottest metal from the ladle. The ladles can be reused. For this, once cold, any skull is removed. It can then be painted with mold wash or prime slurry prior to re-heating for the next campaign.

Summary & Advantages

- ***CLEAN METAL***

The ladle is tilted back to “stick” any slag, then tilted forward to the full horizontal position allowing only the bottom metal to exit.

- ***MINIMAL EXPOSURE TO ATMOSPHERE:***

The ladle is practically touching the lip of the mold. As the metal fills the cavity, expanded gases exit the mold by surrounding the stream of metal, protecting it by having an extremely low mass.

- ***AVOIDS OVER-POURING:***

Typical ladles take time for the operator to react from when the pouring cup is observed as being full until the moment the flow is cut-off. The Cyclops ladle does not, as it carries only one shot or dose of only the amount of required metal for the casting. Over-pouring adds up pretty fast in handling costs

- ***EVEN POURING STREAM:***

Pouring with a traditional ladle is normally done by "slam pouring" while the Cyclops maintains the same flow rate throughout the pour.

This avoids air entrapment and allows gases to freely leave the cavity instead of "bubbling" out with its further disadvantages.

As soon as the cavities are filled, they start to solidify while the riser or pouring bars are still being filled, allowing for better feeding and improved soundness by making a "hot riser" effect.

- ***LOW HEIGHT FROM MOLD:***

Typically, the stream of a ladle is a cascade that hits the mold hard. This can create unnecessary erosion, splatter, and turbulence during the pour. The atmospheric contact with the stream is also kept to a minimum.

- ***LOWER THERMAL SHOCK:***

Achieved through filling slowly instead of "slam pouring".

Future work

At a given set power, temperature and time Interval, an induction furnace can be fed with preheated bar stock weighing the same as the amount of metal to be dispensed into the next mold. The bar stock goes to the bottom and while it gets melted, the furnace is tapped into the Cyclops ladle.

The next mold to be poured, is put in front of the Cyclops ladle by means of a carrousel or a straight conveyor making a cyclic automated pouring station

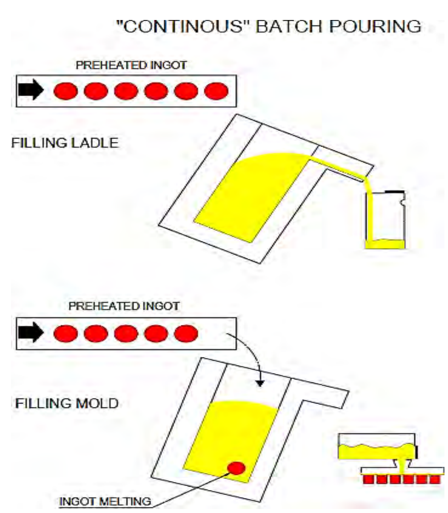

Figure 7. Concept of "continuous" batch pouring

INVESTMENT CASTING INSTITUTE

Novel Regular Ceramic Filter for The Lost Wax Applications

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70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 11

Novel regular ceramic filter for the lost wax applications

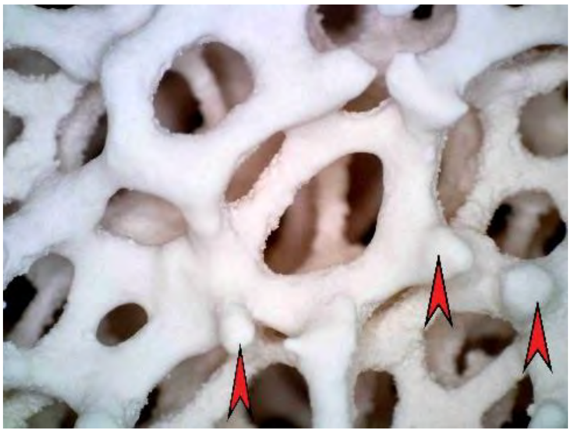
Ladislav Tomek, Jiri Sedlacek, Jan Ondrasek

LANIK s.r.o.

Presented paper describes novel regular ceramic filter type for usage in the lost wax foundries. Regular structure filter type presents a new type of filter determined for the filtration of molten metals as superalloys and steels. Its unique structure is made of circular elements that create the paths labyrinth. It gives a high efficiency to calm the turbulent molten metal flow and provides metal laminarization. There have been done tests on the water simulator proving that behaviour, as well as numerical simulations. Thanks to its regular structure, the described filter enables a repeatable way of application giving almost the same conditions for mould filling - pouring time, dynamic conditions, filling speed. The unique structure of the regular filter is printed on a 3D printer by the SLA technique and final ceramic body is coated on the resin structure or might be produced by direct 3D ceramic printing techniques.

1. Development motivation

- the most demanding application of ceramic filters requires exact, predictable, and repeatable casting conditions
- the regular structure may help to fulfil the requirement
- lost wax process belongs to the most demanding ones – especially in case of zirconia filters and direct pouring



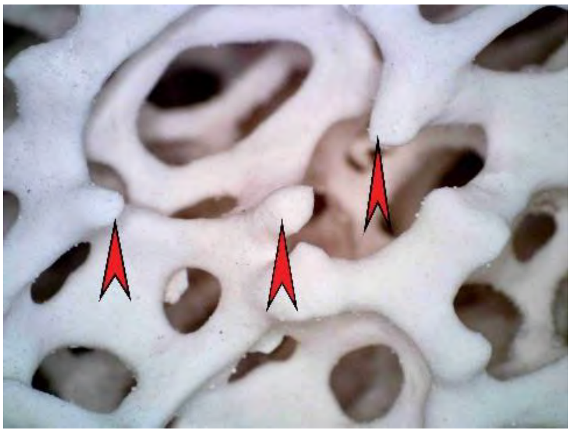


Fig. 1 - Fig. 4. Examples of filter loose ends and filter solutions to prevent losing of free ends (ceramic side edge, fully blocked filter side and fibre gasket).

2. Ceramic Foam Filter vs. Regular Structure Filter

A. Ceramic Foam Filters

- ceramic foam filters use as their skeleton a reticulated polyurethane foam. Its typical property is partially random porous structure and pore size
- loose ends of foam fibres and their potential breakage, can cause secondary inclusions
- randomly built pores within a PUR structure, pouring parameters can vary
- difficult simulations (demanding foam filter calculation)

B. Regular Structure Filter

- Regular Structure Filters are an example of the structure created on with the help of 3D printer. It is typical with a regular geometrical structure, which provides repeatable, predictable pouring conditions and can be applied for simulations.
- Geometrically regular structure
- Repeatable pouring conditions
- Limited free ends, low risk of „snowing‟ (losing ceramic particles) and breakage
- Feasible simulations/structure calculation
- Higher price / demanding production

3. Ceramics of Regular Filter Partially Stabilized ZrO_2 by MgO (PSZ.MgO)

The transformation from tetragonal to monoclinic is rapid and is accompanied by a 3 to 4 percent volume increase that causes extensive cracking in the material. This behavior destroys the mechanical properties of fabricated components during cooling and makes pure zirconia useless for any structural or mechanical application. Several oxides which dissolve in the zirconia crystal structure can slow down or eliminate these crystal structure changes. Commonly used effective additives are MgO, CaO, and Y_2O_3. With sufficient amounts added, the high temperature cubic structure can be maintained to room temperature. Cubic stabilized zirconia is a useful refractory and technical ceramic material because it does not go through destructive phase transitions during heating and cooling.

- pure zirconia exists in three crystal phases at different temperatures
- at very high temperatures (>2370°C/ 4298 °F) the material has a cubic structure

- at intermediate temperatures (1170 °C /2138 °F to 2370 °C/ 4298 °F) it has a tetragonal structure
- at low temperatures (below 1170°C /2138 °F) the material transforms to the monoclinic structure

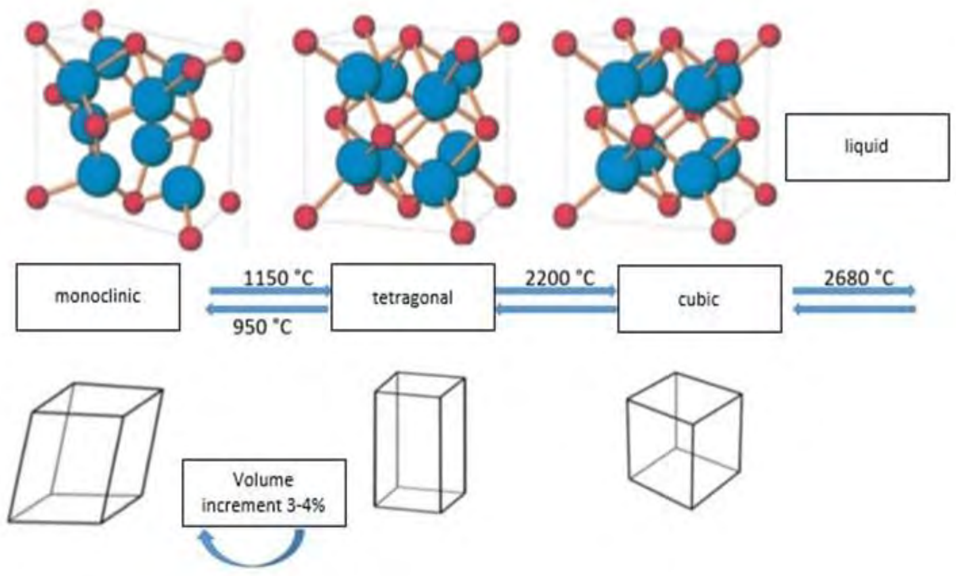


Fig. 5. Phase changes of ZrO_2 during heating and cooling stages.

4. ***Regular Structure Description***

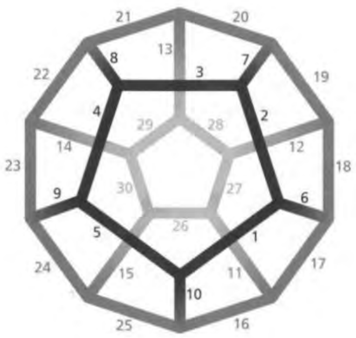


Fig. 6

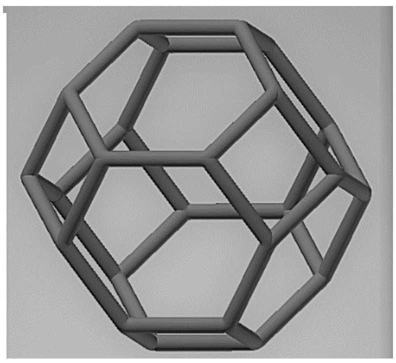


Fig. 7

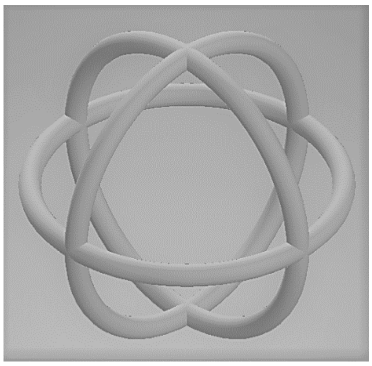
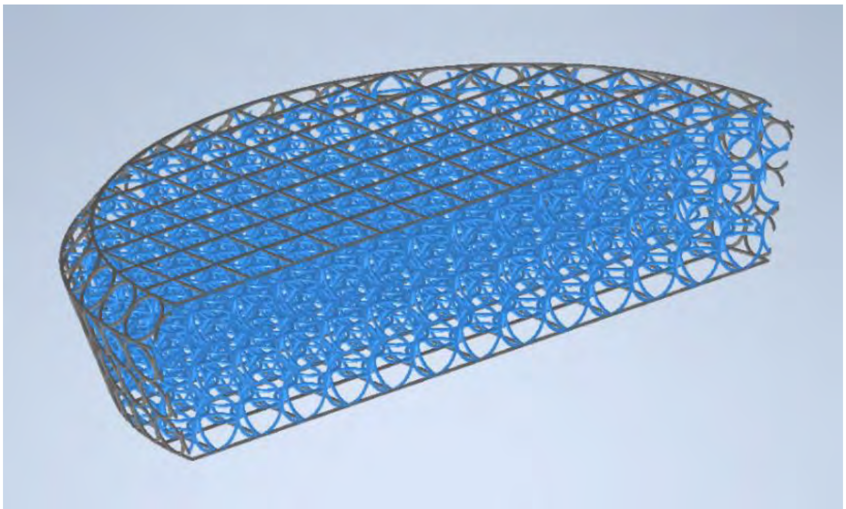


Fig. 8

Dodecahedron Cell (Fig. 6) - Basic unit of a foam filter structure. Idealized structure, non – connectable for making full structure

Kelvin structure (Fig. 7) - Is a symmetrical system of cells formed by hexagons forming the edges of the cells

LANIK's structure (Fig. 8) - Is a symmetrical system of cells formed by circles forming the edges of the cells



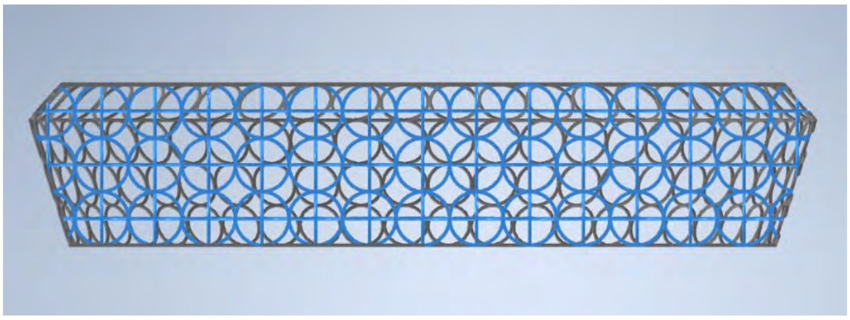


Fig. 9 and Fig. 10. Examples of designed regular structure filters.

5. Regular Structure Filter Production

The unique structure of the regular filter is printed on a 3D printer by the SLA technique and final ceramic body is coated on the resin structure or might be produced by direct 3D ceramic printing techniques. Both production techniques are under consideration and development for designed structures.

6. Numerical Simulations

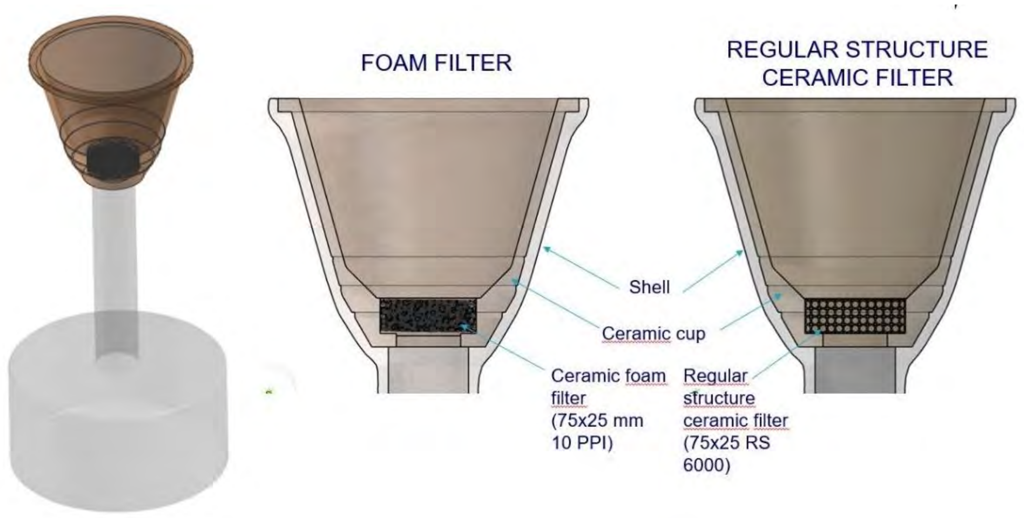
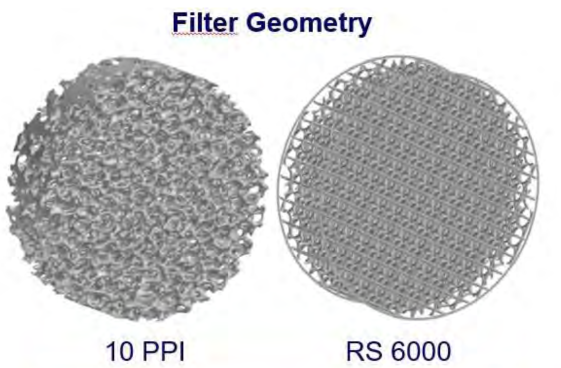
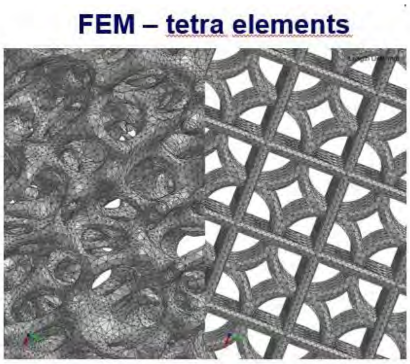


Fig. 11. Simulated virtual assembly.



Parameters	Value
Casting material	Inconel 713LC
Pouring temperature:	1450°C (2642 °F)
Initial shell and filter temperature	900°C (1652 °F)
Metal flow rate	7kg/s



	Foam filter	Regular filter
Nb. Nodes	2118189	2053936
Nb. 2D elements	107914148	1060350
Nb. 3D elements	12499061	14413097

Fig. 12. Filter geometry and conditions.

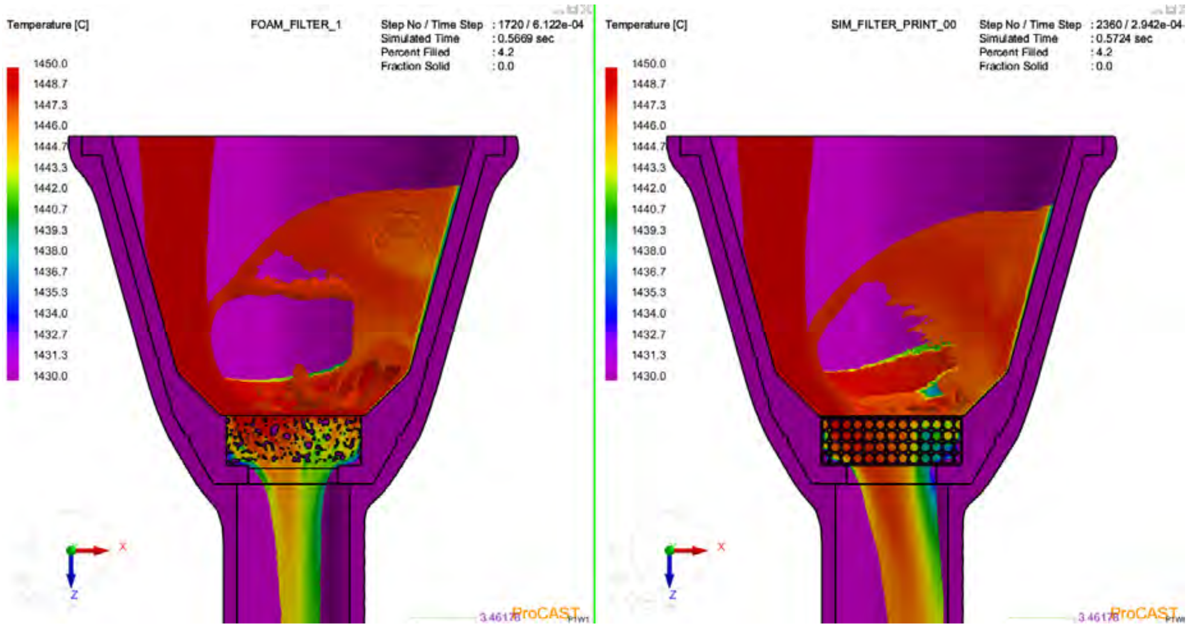


Fig. 13. Temperature Loss - *beginning of metal pouring.*

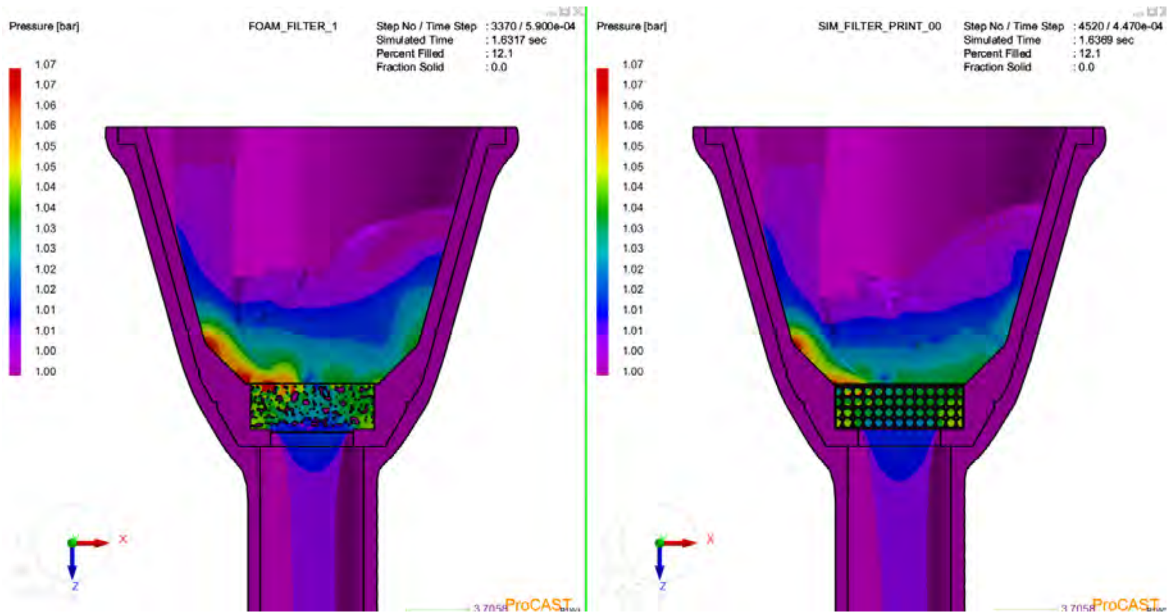


Fig. 14. *Pressure drop during metal flow.*

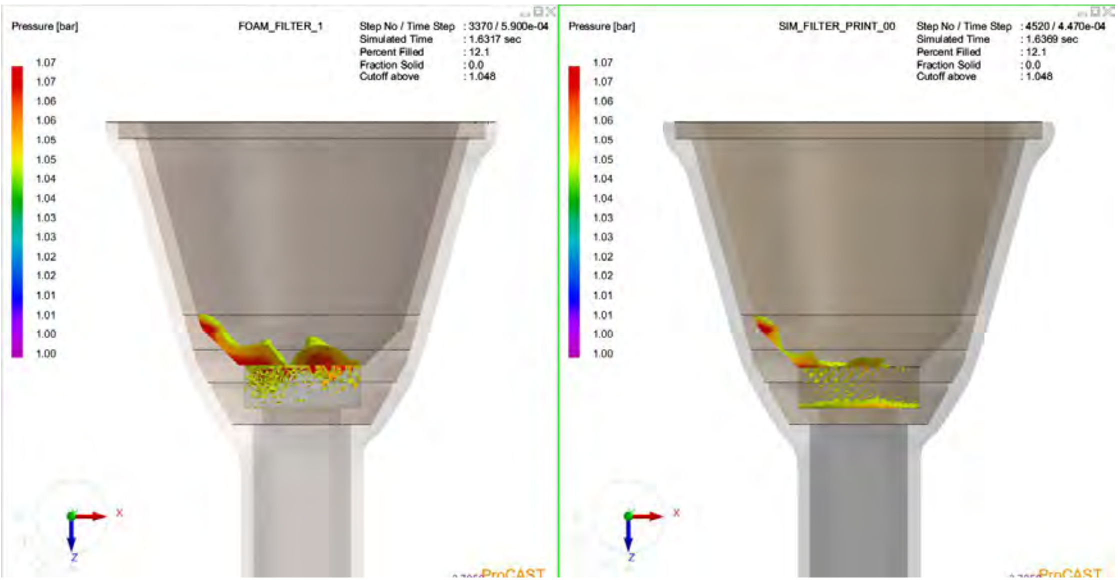


Fig. 15. *Pressure above the cut-off value.*

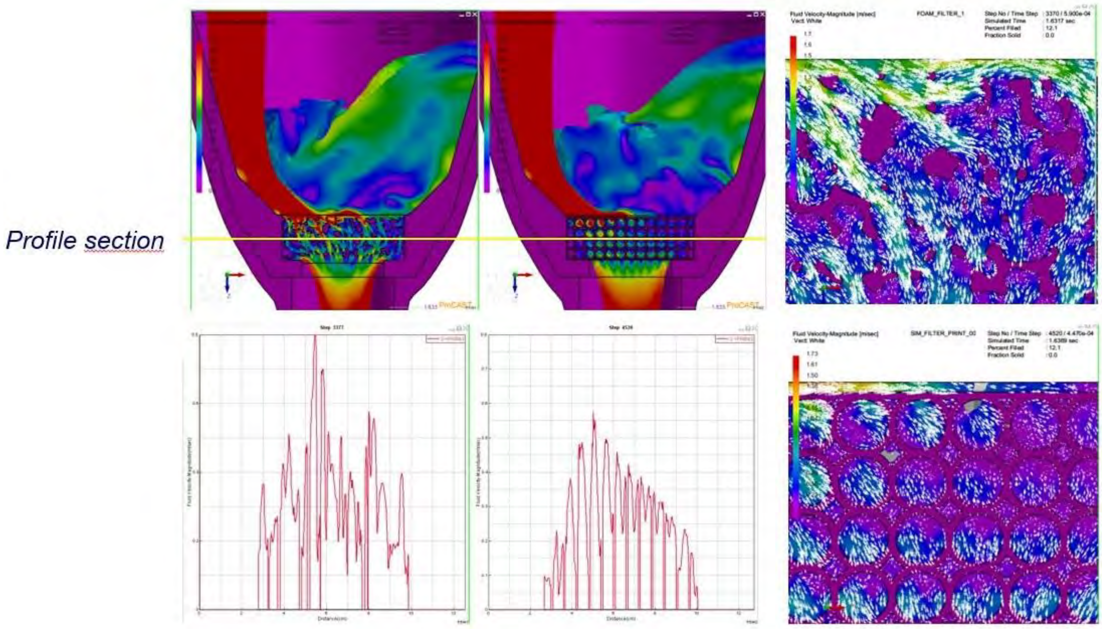


Fig. 15. *Metal velocity profile vectors – in the middle of the filter*

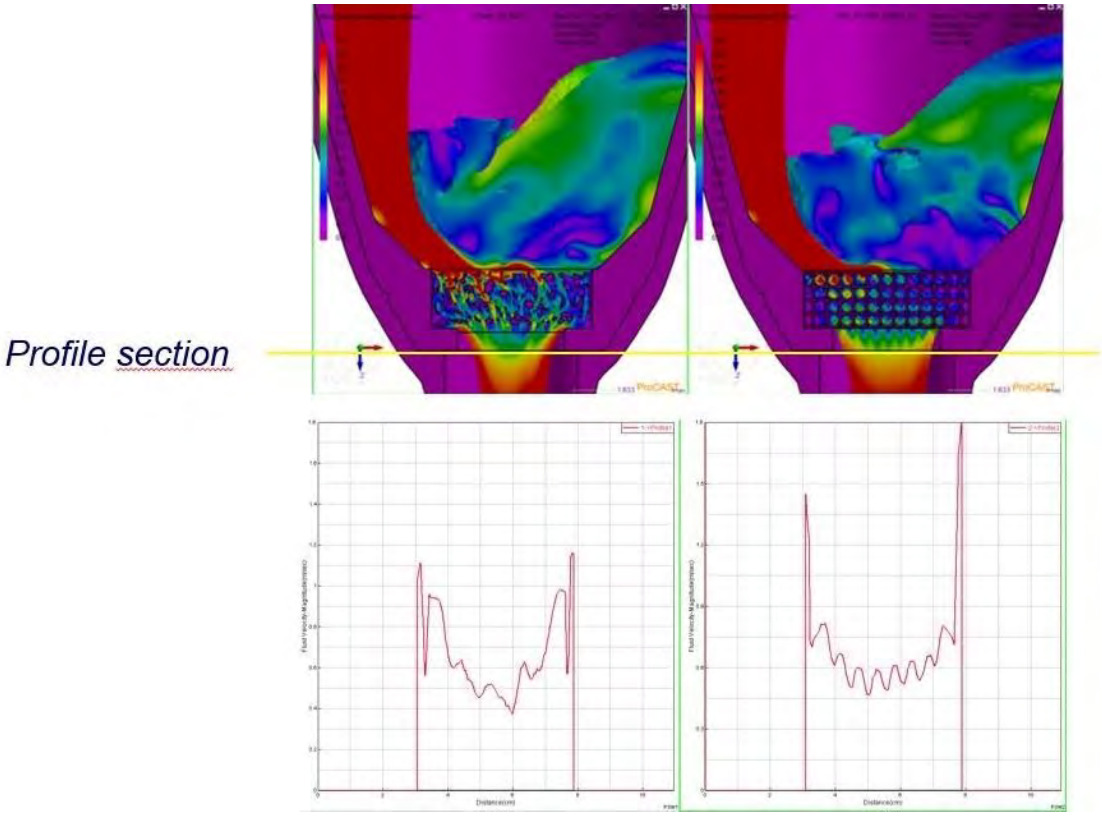


Fig. 16. *Metal velocity profile vectors – behind the filter*

7. Summary

- LANIK's Regular Structure Definition
- Alternative to 10 PPI ~ RS 6000
- Alternative to 20 PPI ~ RS 5000
- RS Filters - very good compression strength and dimension accuracy
- Numerical simulations – foam filter vs. regular structure
- Future works – fractal and complex geometries definition

INVESTMENT CASTING INSTITUTE

Effect of Depressurization on Dimensional Expansion of Turbine Blades Casting Process

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Tubitak Marmara Research Center

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper No. 12

Effect of Depressurization on Dimensional Expansion of Turbine Blades Casting Process

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Keywords: Turbine blades, Investment Casting, Supperalloys, 3D scanning, Depressurization

Abstract

In this study, improvement studies were carried out with the aim of reducing the dimensional expansion in turbine blades after casting. The production of turbine blades starts with the process of forming a shell by coating ceramic slurry on the turbine blades. These shells are produced with the help of wax injection and then discharging the wax from the shell with an autoclave system without damaging the ceramic coating. Overall process directly affects the casting in terms of dimensions. The shell layers that separated or cracked from the blade surface in autoclave cause dimensional differences and reduce production efficiency. In particularly, the cracking and/or expansion of the first layer of ceramic shell causes dimensional differences as well as many other defects such as surface defects and flashes. That's why their removal is necessary in order to comply with aviation standards in turbine blade production. For this purpose, it is aimed to improve the process parameters in this study, to reduce the scrap rate. The motivation of this study was carried out on the depressurization rate which is also a significant parameter of autoclave. Two different depressurization rate were investigated. Two shells with same blade geometry were coated, dried, de-waxed, fired, cast and heat threated under same conditions. First shell was applied a depressurization rate of 0.5 bar/min. and the second shell was applied 4 bar/min. After blades were cast dimensional expansion and tolerances were checked by 3D scanning method via GOM. It was observed that 0,5 bar/min. depressurization rate showed better dimensional tolerances on airfoil thin wall thicknesses under same process conditions.

1. Introduction

Investment casting(IC) is a metallurgical process widely used for the production of metal components for many applications such as automotive, power gas turbines, plane engine parts like hot zone working turbine blades complicated with cooling geometry and near-net-shape parts of high-performance materials [1]. The very first single crystal turbine blades were manufactured by wrought methods. Over the years, increasing demand on high temperature working conditions, design complexity, cooling inner zones and structural integrity led aviation industry to develop superalloys via investment casting technology for turbine blades [2]. Investment casting produces precise components while minimizing material waste, energy, and subsequent machining. It provides extraordinary dimensional accuracy among other casting methods which is approximately 0.5% or even smaller range. The progress over the years in dimension control has given a continual improvement in turbine blades airfoil casting[3]. It is also important to keep dimensional accuracy starting from wax injection process, shelling, de-wax and firing before casting. Besides, following factors can impact on dimensional changes such as; Pouring temperature, casting geometry, mould temperature, alloy, metallostatic pressure, insulating chills, surface roughness and thickness of the shell[4]. In literature, it is known that shelling conditions such as temperature and humidity are critical for having sufficient green strength on investment casting shells which mostly prevents the shell from cracks, flashes, expansion and so on[1], [5]. Autoclave is a process which melts the wax from the shell and create a cavity for pouring the metal. This process has impact on cast defects such as flashes, cracks and expansions. Kevin Lee (2015) showed in his study that the effect of autoclave parameters depends on drying conditions of shells[1]. Synder et. Al(2003) claimed that shell cracks has a negative influence around %20 after their production and %80 during de-waxing autoclave[6]. Mueller(2007) et al. found that the reason of the cracks during de-waxing in autoclave are due to low green strength of shells, sharp corners on wax model, high melting point of wax material, low permeability of shells and/or high depressurization rates [7]. Michael(2022) suggested in his study that low depressurization rate prevents the residual water boiling hence, prevent the micro cracks of shells during autoclave[8]. Overall, the aim of this study is to investigate the dimensional accuracy effect of different depressurization rate in autoclave process. Hence, turbine blade models were shelled, sintered, casted and heat threated under same conditions. Finally, blades were measured and analyzed by 3D scanning method aka GOM which is a digital photogrammetry method.

2. Experimental Procedure

In this study, a simple turbine blade geometry was chosen which was modelled by TUBİTAK MRC for research purposes. A wax (Remet U.K Ltd. United Kingdom) was used to create wax patterns by using injection tooling. The high-pressure turbine blades were manufactured by wax injection process with same injection parameters and wax models were chosen according to GOM scanning results. Two section were chosen for controlling dimensional accuracy that are section A Figure 1 and section B Figure 2.

The chosen blades were with in tolerances ± 0.15 mm on airfoil section. The chosen blades were assembled on two different assemble tree so that shelling can start.

The shelling slurry based on zirconia powder (-200#), colloidal silica binder, wetting, and antifoaming agents. The assemble trees were dipped in slurry which was optimized to reach desired shell thickness. The high-pressure turbine blades were then assembled to assemble tree. Two assemble tree dipped at the same way.

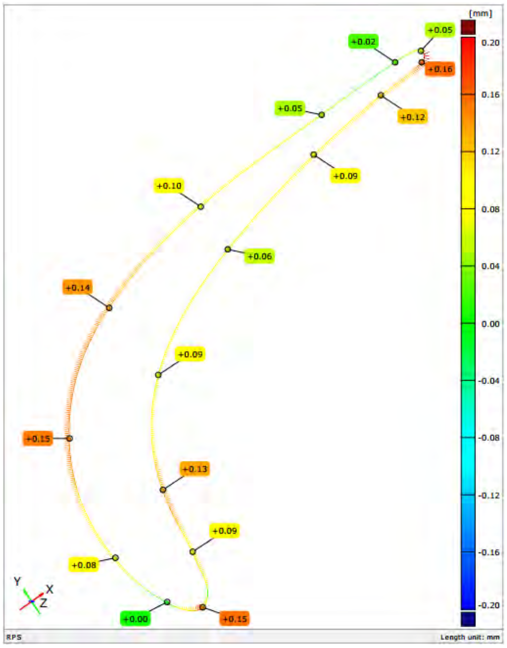

Figure 1. Section A of wax pattern

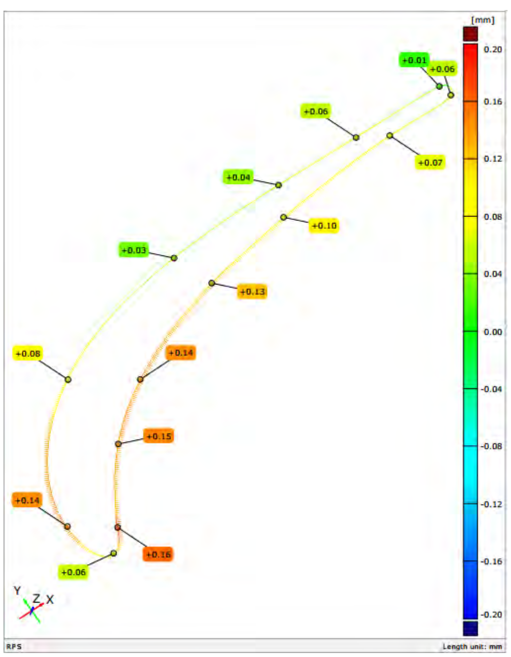

Figure 2. Section B of wax pattern

The processing of slurries and dipping were carried out under controlled room temperature (RT) at 22 ± 2°C and relative humidity (RH) of 50 ± %5 for enhanced homogenization and complete wetting of zircon slurry. The drying conditions were carried out under controlled temperature (RT) and relative humidity (RH) to reach better green strength. During the coating of two assemble tree, the test bars for MoR test were also carried out. The bar samples of size 60x20x8 mm were prepared and tested by flexural strength testing (*aka three point bending test*) for both green and fired strength. Seven samples were tested by using Zwick / Roell Z600, Load Cell: 10 kN Preload 10N and average strength were calculated. Flexural strength testing were carried out at a crosshead speed of 1 mm/min.

Dewaxing of shell moulds was carried out in a closed vessel Quicklock Boilerclave of Leeds and Bradford Boiler Co Ltd (LBBC) with a steam pressure of 8 bar, at 180°C for 15 min. Two different depressurization rate were carried out for de-waxing of shells; first one was 0.5 bar/min, second is 4 bar/ min. The dried shell moulds were kept on a trolley upside-down and then trolley pushed into the de-waxing chamber immediately. The door was closed and the steam was released into the de-wax chamber. To prevent possible shell cracking, the placement of shells and pushing trolley into chamber was carried out in total 15 seconds. The shells were fired after de-waxing for getting rid of any residual wax parts.

Casting of CMSX4-SLS nickel-based superalloy (Cannon-muskegon, USA) was carried out at 1530 °C ± 5°C by using vacuum induction melting furnace (ALD, GERMANY). The shells were heated to same temperature as casting. The parts were cut off from assemble tree and applied standart heat-treatment. Dimension and tolerances of single crystal turbine blades were measured via GOM(Germany) triple Scan 16M model 3D scanner . To get first insight and to see the difference clearly, local-fit method were carried out on airfoil. It can be seen from Figure 3 that the position of reference dots put on each 1mm distance section only. That's why airfoil was the focus point for dimensional accuracy and the rest of dimension and tolerance on turbine blade may not provide the reality due to local-fit on airfoil.

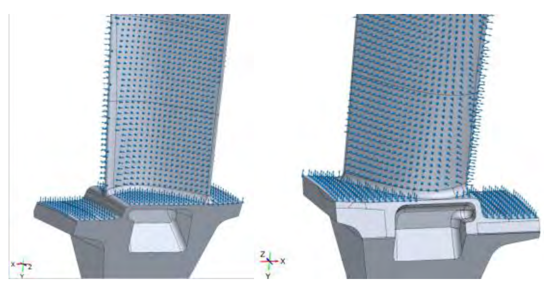

Figure 3. Reference points on airfoil section

3. Results and Discussion

During the shelling procedure, optimized slurry were used for coating of assemble tree layer-by-layer. It was applied until desired thickness obtained. Also test bars were prepared along with assemble trees to define the green strength as it is known as one of the major affect of shell cracking, micro cracks, expansion and so on[5]. The target was to apply similar procedures on two shells so that only difference is two different depressurization rate can be investigated. The flexural strength testing results is given at Figure 4. According to the results, the test bars has shown variation within an acceptable range. The average green strength was measured 5,92 MPa, average fired strength was 5,52 MPa.

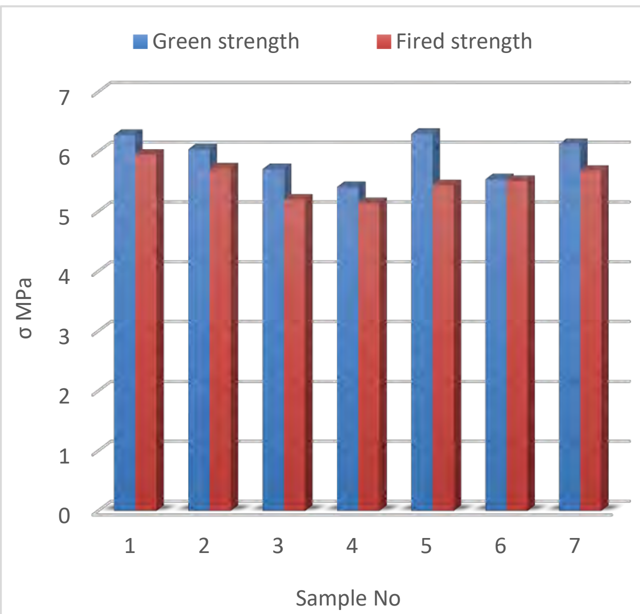

Figure 4. MoR results of test bars

De-waxing of shell moulds were carried out in two different autoclave batches so that two different depressurization rate can be applied. Nothing else were placed into the closed vessel to avoid any affect. First mould applied 8 bar pressure and 0.5 bar/min depressurization rate, the pressure was released in approximately 16 mins. Second mould applied 8 bar pressure and 4 bar/min depressurization rate so the pressure was released in approximately 2 mins. No visible cracks were observed after trolley were taking out after each de-waxing process. Microcracks were controlled after sintering with methylene blue liquid and no microcracks were observed. Sintered shell moulds were prepared for casting of single crystal turbine blade at 1530 °C and heated to the same temperature as casting to control thermal gradient. It was observed there was no leakage during casting and both shells were stable after casting as seen at Figure 6. Then, turbine blade parts were cut off from assemble tree and heat treatment were carried out.


Figure 5. Cluster, shell before de-wax and after sintering

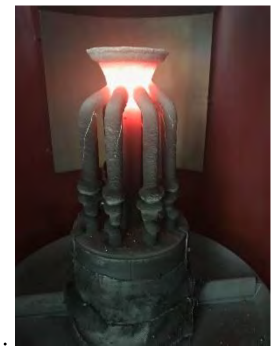
Figure 6. shell after casting


Figure 7. Turbine blades after casting

Turbine blade parts were measured by GOM for dimensional accuracy after heat treatment. The scanning results of two different depressurization rates are given below. The sections taken from airfoil are shown at Figure 8.

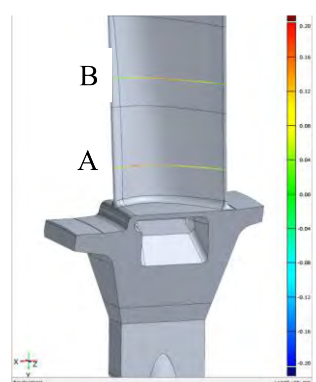

Figure 8. Section A and Section B on airfoil

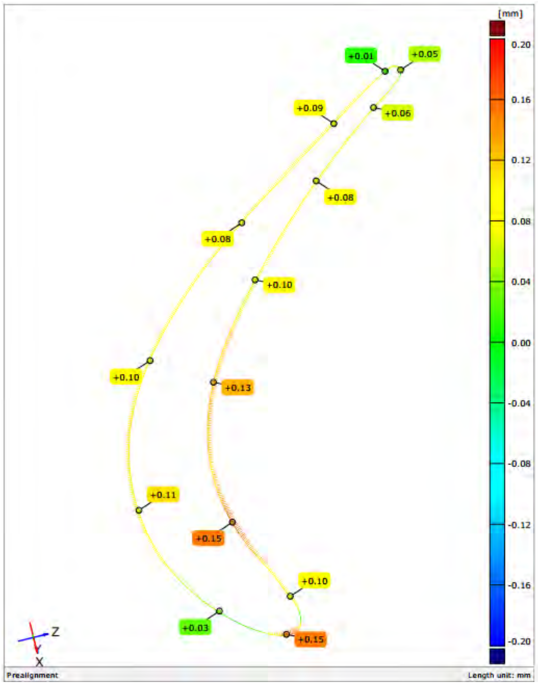

Figure 9. Section A Depressurization rate 0.5 bar /min.

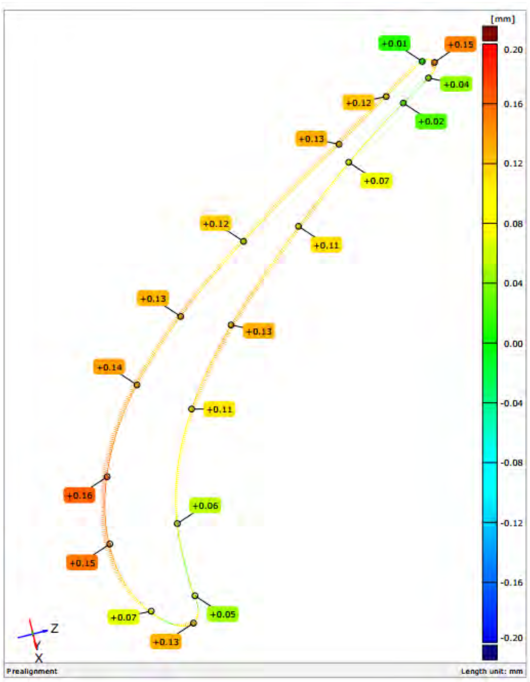

Figure 10. Section B Depressurization rate 0.5 bar /min.

Two different section were taken on airfoil section so that the dimensional difference can be observed. Section A of turbine blade that was applied depressurization rate 0.5 bar /min. given at Figure 9 and Section B of turbine blade that was applied depressurization rate 0.5 bar /min. given at Figure 10. Section A of turbine blade that was applied depressurization rate 4 bar /min. given at Figure 11 and Section B of turbine blade that was applied depressurization rate 4 bar /min. given at Figure 12.

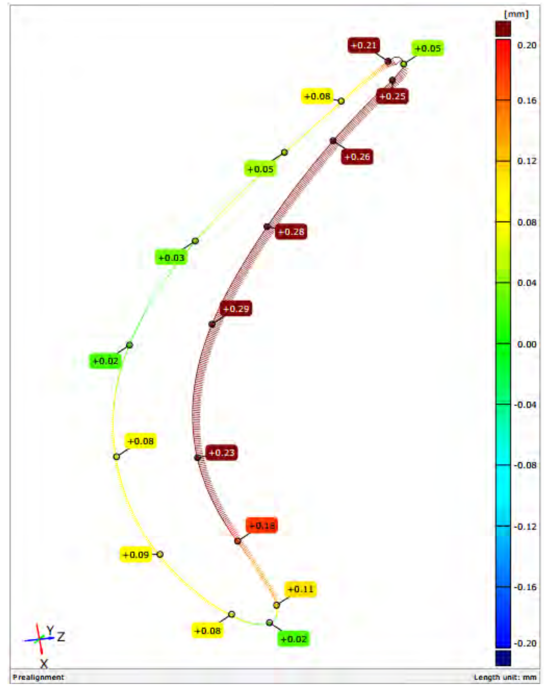

Figure 11. Section A Depressurization rate 4 bar /min.

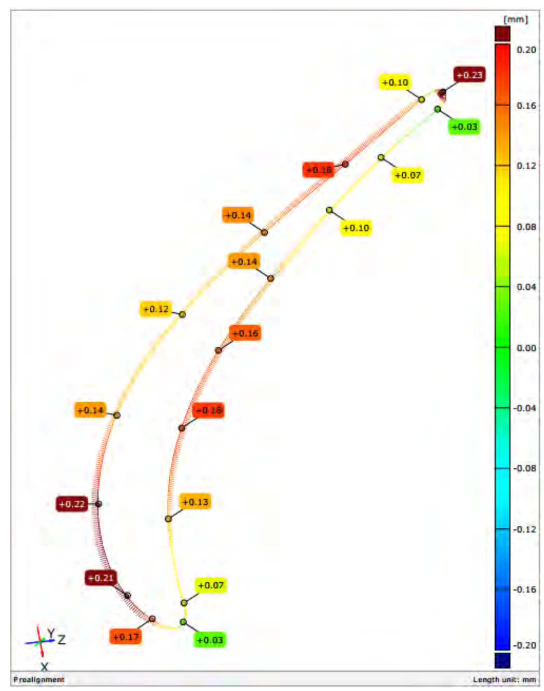

Figure 12. Section B Depressurization rate 4 bar /min.

The profiles of turbine blade with depressurization rate 0.5 bar /min. were observed clearly within acceptable tolerances with a tolerance of ± 0.15 mm both at section A Figure 9 and Section B Figure 12. However, the profiles of the turbine blades with depressurization rate of 4 bar /min. were observed not within the tolerances ± 0.15 mm but within ± 0.30 mm on section A Figure 11 and ± 0.24 mm on section B Figure 12. Moreover, it was beyond the tolerances. It is observed that there is clearly an increased section with the one who applied depressurization rate of 4 bar/min., which is also reason of bulging and expansion in turbine blade.

4. Conclusion

In this study, only depressurization rate was focused on for the de-waxing of autoclave process and all other parameters were kept same for both shells. It has known from literature that the green strength of shell moulds has an impact on dimensional accuracy [1], [5], [9]. According to 3D scanning GOM results; depressurization rate 0.5 bar /min at section A Figure 9 and section B Figure 10 has shown better dimensional accuracy within the tolerances of ± 0.15 mm whereas depressurization rate 4 bar/min. showed increased thickness of turbine blade on section A and section B. It is clear that by producing shell moulds under same conditions, depressurization rate has impact on dimensional accuracy.

Acknowledgement

The authors are grateful to Tübitak Marmara Research Center colleagues who contribute on this study support and the provision of laboratory facilities.

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INVESTMENT CASTING INSTITUTE

Advanced Electrode Melting for Highest Purity Cast Parts

Dr. Samuel Bogner
ALD Vacuum Technologies GmbH

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 13

Advanced Electrode Melting for Highest-Purity Cast Parts

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Abstract

Electrode Induction Melting Inert Gas Atomization (EIGA) is the state-of-the-art process for high-quality spherical powder production. In the EIGA process the lower end of the vertically hanged pre-alloyed electrode is continuously fed into the region of high-frequency electromagnetic (EM) field created by a conical coaxial induction coil located below. Induction melting takes place and a flow in a thin layer is formed at the conical tip of the electrode resulting in a metal down-stream on the axis. The application of electrode induction melting for investment casting could be exceptionally beneficial for achieving the highest cleanliness of the cast parts. However, the electrode induction melting for metallic powder production is currently a well-established technique only for relatively small melt rates (such as <2 kg/min). On top of that, the melt cannot be significantly superheated due to the small thickness of the liquid layer at the conical electrode tip and the fact that material instantly leaks out of the zone of EM heating as it turns liquid due to the gravity and pinching Lorentz forces. In the present work, we are using numerical modelling and experimental validation to demonstrate how the high-melt-rate and high-superheat electrode induction melting can be designed for investment casting applications.

Introduction

The Electrode Induction Melting Inert Gas Atomization (EIGA) process was developed and patented by ALD Vacuum Technologies [1] as a ceramic-free atomization process that is especially suited for production of high-purity, reactive and refractory metal powders (Fig. 1a). In the EIGA atomization process the pre-alloyed cylindrical electrode (< Ø150 mm and < 1 m length) is mounted on an electrode feeding device which continuously lowers the vertically hanged electrode into a conical induction coil. Then, energy is coupled into the electrode tip using a high-frequency electromagnetic (EM) field. As a result, a melt film is formed on the electrode surface and a molten metal stream or droplets fall from the electrode tip into the inert gas nozzle where a high-velocity gas stream atomizes the melt [2]. By this means, the generated micro-droplets solidify while traveling down in the atomization tower and form spherical shaped fine powders which are collected in a vacuum-tight powder container.

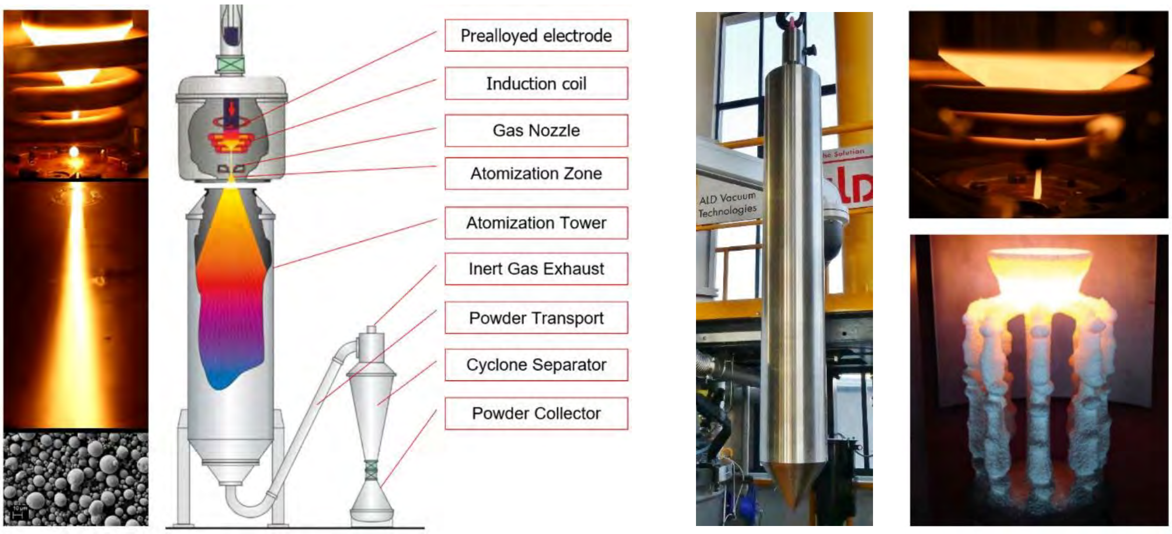
Our goal is to investigate if the advantage of crucible-free electrode induction melting can be combined with Investment Casting (Fig. 1b). In this case, a melt stream with sufficiently high superheat and a melt rate of 60-120 kg/min for typical Direct Solidification or Single Crystal process has to be created.

The main advantage of the EIGA-type electrode melting for Investment Casting is that it is crucible-free. There is no consumable part that has to be regularly replaced and might be a source for ceramic impurities found in castings. Therefore, the guarantee of an ultimate casting purity is a clear advantage. On top of that, the EIGA-type electrode melting is very easy to operate. If sufficient power is applied, the system finds the steady-state itself and runs in a self-sustained stable mode. Using an electrode as a feedstock material can save a lot of time - no need of charging and discharging the one-shot liner in the back-up crucible. Electrode melting can be stopped anytime and continued later on using the next mould. Apart from that, alloy manufacturer already casts and delivers material in form of cylindrical electrodes and foundries have to cut the ingot in order to fit it in the one-shot liner. Additional impurities caused by this step, approximately 2% of material loss and expenses for the ingot cutting could be saved.

On the other hand, electrode melting at a high melt rate requires high power generators that could be quite expensive. However, EIGA-type melting due to high efficiency still can offer an opportunity for the energy saving in the long-term.

Keeping this in mind, this work focuses on the feasibility study and reveals if it is possible to achieve a high melt rate and a high superheat melt stream required for Investment Casting applications. Currently well-established melt rates used for powder atomization are below 2 kg/min. Moreover, it is known that during EIGA-type electrode melting the melt instantly leaks out of the zone of EM heating (small residence time) via thin layer. The achieved superheat is low and this might be a fundamental issue for the casting applications even if higher melting rates are achievable.

Direct melt stream superheat measurement is barely possible, therefore, we have developed and verified a simulation tool that precisely describes EIGA-type electrode induction melting [3]. According to simulation results, a melt stream superheat reaches 40 C during Ø150 mm Ti64 electrode melting at a rate of 2 kg/min (Fig. 2). Insufficient superheat is indirectly confirmed by formation of flakes instead of powder in powder atomization experiments.



(a) (b)

Fig. 1. The EIGA process and a well-established atomization of Ø50 mm Ti64 electrode at a melt rate of 1 kg/min (a). The idea of EIGA-type Ø150 mm Ti64 electrode melting for investment casting application (b)

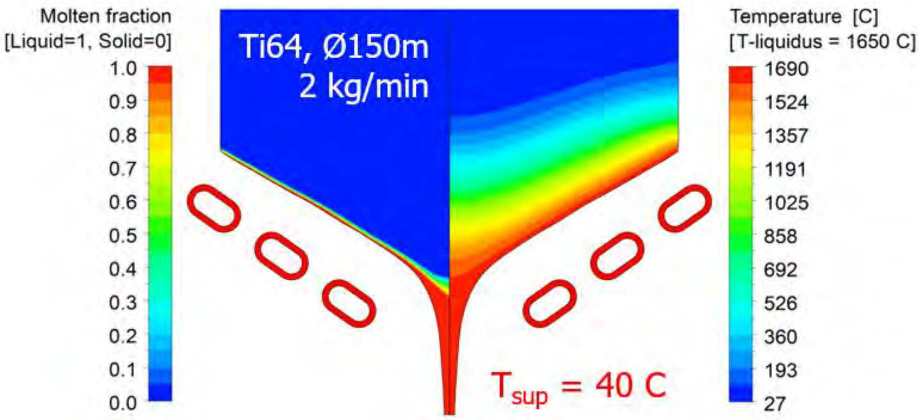


Fig. 2. Simulation results of the EIGA-type electrode steady-melting at 2 kg/min for powder atomization that reveal low melt stream superheat of 40 C. Contours of molten fraction are shown on the left (fully solid = blue, fully liquid = red) and temperature distribution on the right

Results of numerical modelling

1) Melt rate

An important parameter that is kept constant for further parameter study is the gap between the coil and electrode tip (controlled by inductance value in EM problem), because this distance determines the melting efficiency.

Simulation reveals that increase of the melt rate leads to a favourable increase of the volume-averaged melt stream superheat (Fig. 3). Note the large superheat of almost 250 C that can be achieved for Ti64 Ø150 mm electrode at a melt rate of 10 kg/min.

Let us take a look on the steady temperature profile in the electrode (Fig. 4). Somewhere far away above the melting front the electrode is cold, let's say at a room temperature. However, closer to the melting front the temperature rises and reaches the liquidus temperature at the melting front. Now, for simplicity of explanation, let us neglect thermal conductivity dependence on temperature and the latent heat. If the heat flux is flowing through the melting front, there must be a temperature gradient that drives it through the molten layer. Or the molten layer temperature at the free surface should be higher than liquidus temperature at the melting font. This is how the superheating still takes place in the molten layer.

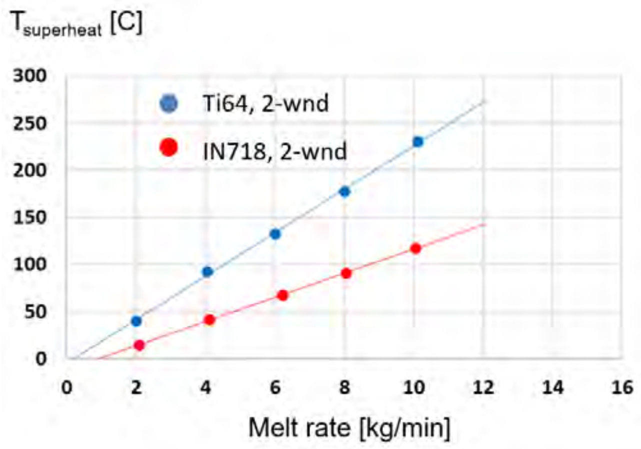


Fig. 3. Steady-state melt stream superheat depending on the electrode melt rate for Ø150mm Ti64 (blue) and IN718 (red) alloys

Now, if we double the feeding velocity (=double the melt rate), and accordingly increase the delivered power (increase the heat flux), the temperature rise in the solid electrode will get steeper (Fig. 4) that will lead to a larger superheat in the melt layer (Fig. 5).

Despite small superheat caused by the small melt rate in case of EIGA powder production, the superheat can be significantly increased by increase of the melt rate.

2) Alloy

Linear dependence of the superheat on the melt rate depends on the alloy thermophysical properties. For example, in case of IN718, we achieve less superheat at the same melt rate, if compared with Ti64 (Fig. 3).

If density is increased (with all other properties kept the same), the same melt rate requires less feeding velocity, and if material moves slower, the higher temperature penetrates deeper in the electrode. So, the temperature gradient is reduced inside the solid electrode and in the molten layer.

Further superheat decrease is achieved with higher thermal conductivity, lower liquidus temperature, lower latent heat, lower specific capacity of the solid fraction, etc. or larger electrode diameter (= slower feeding velocity if the melt rate is maintained constant).

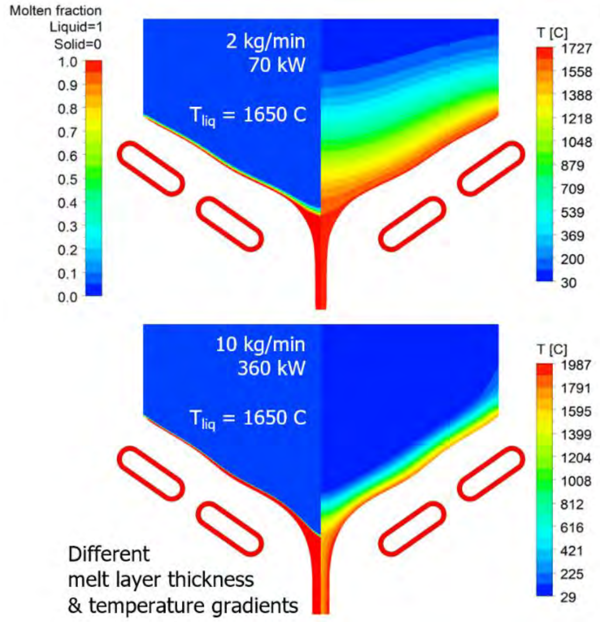


Fig. 4. Contours of molten fraction (on the left) and steady temperature distribution (on the right) in the Ø150mm Ti64 electrode being molten at two melt rates: 2 kg/min (upper figure) and 10 kg/min (lower figure)

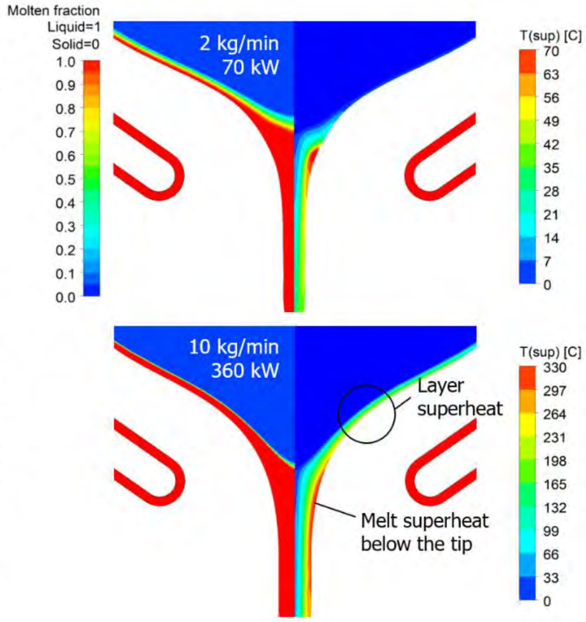


Fig. 5. Contours of molten fraction (on the left) and superheat temperature distribution (on the right) in the Ø150mm Ti64 electrode being molten at two melt rates: 2 kg/min (upper figure) and 10 kg/min (lower figure)

3) Inductor design

Actually, it would be more convenient, if we could set the melt superheat and the melt rate separately.

In this case, design of inductor plays also an important role. Here is an example showing that a smaller number of inductor windings allows us to achieve higher superheat (Fig. 6). All the other parameters, including inductor generatrix and AC frequency are kept the same.

Note that despite the same melt rate, the total power required to maintain the same gap between the electrode and the 2-winding coil appears to be bigger than in case of 4-winding coil. This power difference converts directly in the melt superheating below the tip of the electrode (and has nothing to do with "layer superheat").

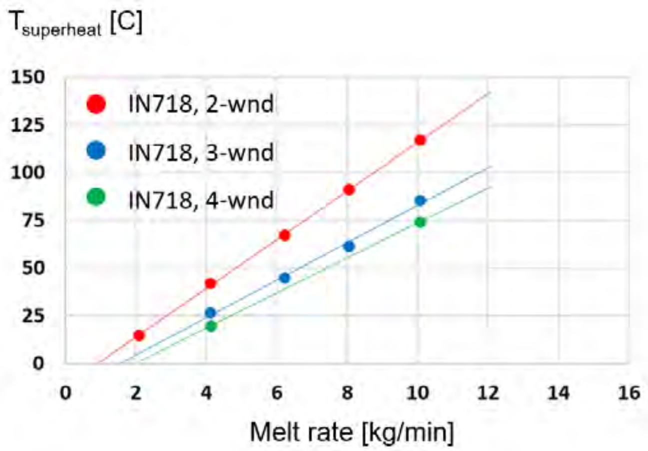


Fig. 6. Ø150mm IN718 electrode (10 kg/min) steady-state melt stream superheat depending on the number of inductor windings (2 - red, 3 - blue & 4 - green)

4) Total power level

Another way how to control the superheat independently from the melt rate is to tune the level of the total power.

Let us think of the following experiment: you are steady-melting the electrode at a low total power level. This means that the net power that you induce in the electrode matches the melt rate (or the electrode feeding velocity). What would happen if we would instantly increase the total power level? In this case we would instantly induce much more power in the electrode. However, keep in mind that we maintain electrode feeding velocity constant. So, you would instantly melt faster than you feed the electrode material and the gap between the coil and electrode would start to increase. If the gap increases, you are inducing less net power in the electrode. The gap will be increasing so far unless the net power in the electrode will match again the electrode velocity. This is an amazingly stable and easy to run system that drives itself into a steady regime.

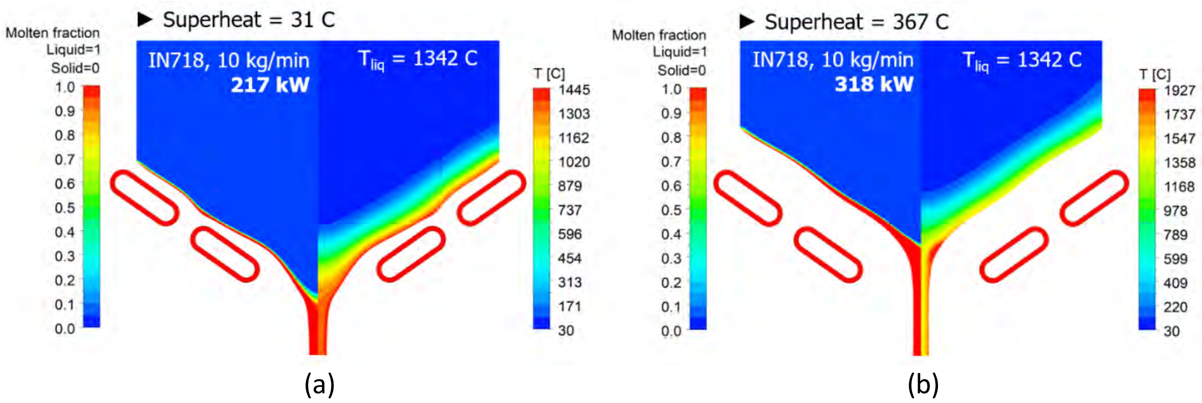


Fig. 7. Contours of molten fraction (on the left) and steady temperature distribution (on the right) in the Ø150mm IN718 electrode being molten at 10 kg/min with two different total power levels: 217 kW (a) and 318 kW (b)

Now if you will melt two electrodes at the same melt rate and different power levels you will achieve smaller superheat in case of lower total power (Fig. 7a) and larger superheat in case of greater total power (Fig. 7b). In this case it has nothing to do with a "layer superheat". In this case you are superheating the stream below the tip of the electrode. Because of greater gap and higher power level the melt falls slightly longer through a stronger magnetic field and this results in a larger superheat.

So even as your melt rate is fixed, you are able to adjust the superheat by tuning the total power as a separate parameter – wide-range contact-free adjustment of the superheat is especially beneficial during large castings (Fig. 8).

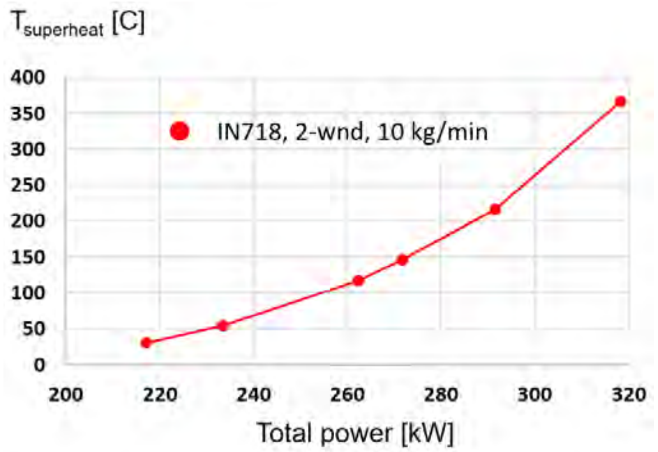


Fig. 8. Steady-state melt stream superheat depending on the total power for Ø150mm IN718 alloy electrode molten at 10 kg/min

Steady-state electrode melting is able to ensure a constant desired superheat, meanwhile, preheating of the electrode tip in combination with increased power at the start of the electrode melting can ensure higher superheat and higher melt rates in the beginning of the mould filling to avoid solidification in ceramic filter or in critical zone next to chill-plate.

Qualitative validation of simulation results

Up to now all the simulation results showed that it is possible to do the EIGA-type electrode melting at higher melt rate and higher superheat. And this brings us closer to satisfaction of requirements of investment casting.

In order to validate simulation results, we decided to carry out demonstrator experiment using a real EIGA powder atomization furnace. We have disassembled the nozzle and placed a copper mould below the coil, and allowed the melt stream to solidify and form a Ø50 mm ingot (Fig. 9a). The surface quality of the ingot would act as a qualitative indicator of the melt superheat.

Note that due to small melt rates used for powder production the generator maximum power was only 100 kW.

► Test 1: the reference setting was 0.5 kg/min of Ti64 at a total power of 40 kW. Note the bad surface quality that indicated that the melt solidified before properly filling the mould (Fig. 9b).

► Test 2: we maintained the melt rate, but increased the total power up to 54 kW. Note the improvement of surface quality that is attributed 100% to a higher superheat (Fig. 9c).

► Test 3: we increased both AC current and melt rate. The surface quality is the best and this is because of two effects: 1) higher superheat due to higher power and higher melt rate and 2) increased thermal inertia due to higher melt rate (Fig. 9d).

To sum up, the experiment using the real EIGA furnace with limited generator power confirmed results of our simulations. Validation experiments with real castings remain to be done.

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

Fig. 9. EIGA-type electrode melting and melt stream solidification in the copper mould for qualitative validation of simulation results (a). Solidified Ti64 ingot surface quality obtained with: 0.5 kg/min and 40 kW (b), 0.5 kg/min and 54 kW (c), 1.0 kg/min and 92 kW (d)

Summary and conclusions

► Melt rates up to 10 kg/min with adjustable superheat between 40 - 400 C were proven using validated numerical modelling. Total power needed to ensure 10 kg/min melt rate is 360 kW for Ti64 and 260 kW for IN718. Even higher melt rates are possible but require proportionally greater power.

► At this stage of the project "Advanced Electrode Melting for Highest-Purity Cast Parts" open points with DS/SX investment casting industry has to be discussed:

- The EIGA-type melt rate (= cast rate) is still a rather low compared to casting rates for DS/SX process of about 60 kg/min or higher.
- Adaptation of the casting system of the DS/SX shell mould cluster to the new melting/casting process.

► If the above-mentioned challenges can be overcome, the EIGA-type electrode melting offers attractive advantages over conventional vacuum induction melting with a back-up crucible and a one-shot liner for the DS/SX process, listed below:

- crucible-free (no wear/no consumables), contact-less melting
- ultimate casting purity
- easy to operate, reproducible, reliable
- electrode allows for higher productivity & flexibility
- higher melting efficiency resulting in a decrease energy consumption for melting

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INVESTMENT CASTING INSTITUTE

An Approach Utilizing Technology to Restore the Metal Casting Industry to a New Level of Pre-eminence

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Paul Finelt, Concurrent Resources LLC

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 14

An Approach Utilizing Technology to Restore the Metal Casting Industry to a New Level of Pre-eminence

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Abstract:
The metal casting industry is one of the oldest, most challenging, and energy-intensive manufacturing processes. It has experienced swift and significant headwinds due to the pandemic. Massive changes in raw material prices, utilization spikes, OEM backlogs, and lack of maintenance availability and human resources are the themes that challenge us today. Further, worldwide developments are continuously changing our operational dynamics.

While our society is excellent at responding to a crisis, we need to be pre-emptive in our approaches and prevent those problems from ever happening. This failure of most organizations to achieve outstanding, innovative results is not surprising. Innovation is a complex topic that is influenced by a plethora of interacting factors. Because of this complexity, it is challenging for organizations to get all of the aspects right at the same time, to provide the results that everyone needs.

The economic superiority of America continues to depend on technology to detect and deter potential aggressions. Such technological capability demands ongoing investment and implementation of innovative manufacturing and product design technologies to preserve our industrial base and grow our technical and economic superiority against strongly increasing foreign competition. The metals casting industry has been one area that has been lagging in advancements due primarily to proprietary interests.

While everyone is looking for that silver bullet that will end all the challenges, the Investment Casting Institute (ICI) Technical Committee has established an Additive Manufacturing Sub-Committee to be a vehicle to help accelerate the understanding and impact of our advanced manufacturing (AM) capabilities and the application of these tools to our casting businesses and supply chains.

To successfully do this, the ICI continues to collaborate and communicate with other industry trade associations. In March of 2023, we conducted our first annual Additive Manufacturing for Investment Casting (AM4IC) Symposium in Cleveland, Ohio. During this event, we charged the industry, and all in attendance, with the responsibility for competitive growth through technological advancement. It was emphasized that the future lies within our control, and that the future is now. It was our intention that this symposium would serve as the inciting action to drive the industry forward.

What matters is what we do today. The past is there for us to learn from. It is a data point and now, leadership must maximize what we are doing with our focus set on what is going to happen in the future.

In this presentation, we will update you on our journey to operational excellence and innovation, and what we are doing to build strong relationships and trust. Cultural change is hard. However, our ability to influence through shared experiences and "doing" will be an enabler for everyone.

INVESTMENT CASTING INSTITUTE

Nadcap Casting Program

Dr. Richard Freeman
PRI

70TH TECHNICAL CONFERENCE & EXPO 2023

Paper № 15

ICI Annual Conference & Expo – 13-16-Aug-2023, Pittsburgh

Nadcap® Casting Program - Dr. Richard Freeman (PRI)

The Nadcap® program started in 1990 and is administered by the Performance Review Institute, who have facilities in the USA, UK, Japan and China. It is industry-managed, bringing together technical experts from the aviation, space and defense industry, as well as government representatives, to establish requirements for accreditation and to accredit Suppliers for critical processes. It is a standardized approach to quality assurance which helps to reduce cost, promote collaboration, and drive flawless performance. The Nadcap® program has 60 Aviation, Space & Defense original equipment manufacturers (OEMs) and Government Agencies with design authority focused on special processor quality assurance as Subscribers, conducts 6,300 audits annually worldwide across 24 critical processes, and has 350 auditors on its books, located in North America, UK & Europe, Japan, China, South Korea and India.

There are very few industry specifications controlling the manufacture of castings, with most OEMs using their own or supplier specifications to control casting and cast parts. General Quality System standards like AS9100 are not designed to provide the depth and breadth needed to address critical casting processes. At the request of Industry, the Nadcap® Management Council approved a Metallic Materials Manufacturing Task Group to address areas such as forgings, castings, and raw materials. The audit criteria for Sand Casting (AC7142) was published in 2022, and the audit criteria for Investment Casting (AC7141) was published in 2023, with audits having started in Q1 2023.

The Audit Criteria was developed with experts from Subscriber OEM companies, including Honeywell Aerospace, Airbus Commercial, Collins Aerospace, Safran Group, Rolls-Royce, MTU, Leonardo Helicopters, BAE Systems and MBDA, as well as Castings Suppliers involved in the Nadcap® program.

The castings audit criteria questions are grouped into sections based on the audit process, and include:

- General requirements (preventative, maintenance, training, documentation, tooling and dies manufacturing and storage)
- Purchase order review
- Purchasing and verification of product (raw material and consumables)
- Tooling design and control
- Tooling manufacture and control
- Core design and control
- Core manufacture
- Wax pattern manufacture
- Wax assembly
- Shelling
- Solid mold process
- Dewaxing (removal of pattern)
- Firing
- Mold prep
- Mold insulation
- Mold pre-heating

- Casting (Raw material verification, Mold transfer, Induction melting, Crucible/pot control, Alloying additions in crucible, Innoculation, De-gassing, De-oxidizing, Slag, Trimming additions, Pouring parameters)
- Control of solidification (Equiaxed, Directionally Solidified, Single Crystal)
- Post cast processing (Shell removal, Blasting (for cleaning), Cut off, Gate witness removal, Surface finishing, Core removal)
- Mechanical testing
- Chemical testing
- Salvage welding (rework weld)
- NDT
- HIP
- Alpha case removal (for Titanium alloys)
- Heat treatment
- Inspection
- Some of the sections listed will be NA as not carried out at the supplier's premises

The job audits include one historic long job audit covering the entire process, and up to 36 shorter in process live job audits, with several of them having NA answers if the process is not carried out in the facility. This audit criteria covers the investment casting of aluminum, nickel, steel and titanium alloys, with audits covering 3-5 days depending on the number of alloy groups cast at the facility.

A Nadcap® casting audit can assist in improving a supplier's quality process. For example, minor nonconformances found in the Forgings commodity during Nadcap® audits have reduced by 50% over the last 5 years, and the number of Forging suppliers with extended accreditation status has doubled since 2020. In addition, Subscribers have reduced their audits of suppliers by up to 33% as a result of the Nadcap® forgings program, and we expect the same to happen in the castings commodity.

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INVESTMENT CASTING INSTITUTE

ICI Process Control Standards & Nadcap Casting Program Complementary Systems with Different Objectives

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Complementary Systems with Different Objectives

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Since the roll out of the Investment Casting Institute's Process Control Standards (PCS) certification program and that of the Nadcap® Casting Standards, there have been a number of members, non-members and customers that have approached the ICI with the question "how do the programs differ?". The fact is the programs differ in a wide variety of areas, but before addressing the differences, it is important to understand the similarities.

Both programs have a focus on three operational areas, the wax shell and casting areas of the foundry. The ICI recognizes that both programs have their place in the industry, although serving different purposes, and both programs offer value to the foundries that participate in these programs. The way in which the programs address operational areas, serve the industry and offer value to participants is where the differences begin.

It is important to understand that the programs were designed with different objectives in mind. The Nadcap® Casting Program was designed to strengthen the aerospace industry. PCS was designed with the objective of fostering foundry growth and advancement, thus strengthening the investment casting industry.

Expanding on this, it is important to understand which companies were involved in each program's design, as the perspective taken of the industry differs from group to group. The Nadcap® program was designed by aerospace industry OEMs for use as a supplier validation tool. The ICI program was developed by investment foundries and industry suppliers with diverse backgrounds. PCS is focused on controlling processes, enhancing yields and reducing scrap due to process variation, that is, this program is designed to serve the needs of the foundry regardless of the market being served.

Since the Nadcap program was developed to support foundry qualification as a supplier, it is expected that this certification will be required by some if not the majority of aerospace OEMs, making the program compulsory for foundries producing aerospace products. ICI Process Control Standards is a purely volunteer program. The only companies using PCS as a measure of performance are the foundries using the tool to evaluate themselves.

Cost has always been a concern of the investment casting industry, for this reason, the ICI set up PCS as a free program to all foundries, regardless of membership status. The only time a foundry will incur a cost is if an independent survey is requested. In those situations, ICI members are responsible for travel and lodging expenses as will as a stipend for the Independent Process Control Certified Surveyor (PCCS). In addition to these costs, Non-Members pay a certification filing fee, while members do not. Nadcap audits have fees associated with them.

Who performs the audit or survey is just as important as what is being reviewed. In the case of the Nadcap Casting Standards, audits are performed by Performance Review International (PRI). PCS surveys are conducted by a certified Internal (foundry employee) or Independent PCCS. Training and certification of Internal as well as Independent PCCS are free of charge. Since PRI performs Nadcap audits, no such training is offered to the foundries, but Nadcap does offer other training programs for a fee.

A Nadcap audit offers a snapshot of how a foundry complies with company documents, while a PCS survey offers a roadmap to the highest degree of process controls. PCS can be applied at the foundry's discretion at a regular or sporadic frequency to measure and improve the quality of the plant's process control systems.

As previously mentioned, both programs address the functional areas of wax, shell and casting. PCS goes a step further and performs an assessment of the foundry's management team. Through interviews with applied labor, supervisors and the management team itself, the visibility and support provided is evaluated. Management awareness of shop floor needs as well as production yields and manufacturing challenges are also assessed by PCS.

The results of a Nadcap casting program audit can have a significantly different impact than that of a PCS survey. Passing a Nadcap audit will result in the plant being certified, and will open doors to working with aerospace OEMs. Failing a Nadcap audit will result in the foundry's certification being revoked. The Auditor will clearly identify areas of deficiency to enable foundry improvement. Failure has a commercial impact in that it may disrupt business with aerospace OEMs.

Passing a PCS survey also results in a certification, but what differs is that there are three levels of certification: bronze, silver and gold. The bronze level, to which a foundry can self-certify, is comparable to passing a Nadcap audit as it certifies that a foundry in compliant with its own policies. Silver and gold certifications go well beyond the basic certification, measuring a foundry's process control systems in comparison to what would be considered "best in class". Structuring the program in this way, foundries have found that PCS supports cycle time reductions, bolsters employee morale and has a favorable effect on the bottom line. The ICI certification can also enhance top line performance as certification can be used as a marketing tool with "bragging rights".

Failing a PCS survey results in either a foundry's certification being revoked or reduced to the level to which they are qualified. Survey results not only clearly identify shortcomings, but that also provide details on the path to self-improvement. This is because PCS employs a scoring system that is both qualitative as well as quantitative in its approach, where each operation's KIVs and KOV's are evaluated against up to six measures, each of which is ranked with a score of 0 to 5. Since the Nadcap casting program was designed to serve a different purpose, it's rating system is binary, or a "Yes / No" system.

In summary, both systems add value to the investment casting industry. The Nadcap® Casting Program is focused on Aerospace OEM and supplier concerns. The ICI PCS program is industry independent, and was designed with the intent of strengthening and growing the investment casting industry through self-improvement. Both programs have their place, yet both are very different from each other in design, purpose and implementation.

To learn more about the Nadcap® Casting Program, contact Dr. Richard Freeman of PRI.

To learn more about the ICI Process Control Standards program, contact the Investment Casting Institute.