Benchmarking Shell Recycling, Productivity Metrics, and Risering Practices in the North American Investment Casting Industry

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ABSTRACT

This paper documents the results of a recent survey of the domestic investment casting industry. It was conducted in support of a research project co-sponsored by the project team and by the Defense Logistics Agency-Troop Support, Philadelphia, Pennsylvania and the Defense Logistics Agency Information Operations, J68, Research & Development, Ft. Belvoir, Virginia. The 26-question survey was intended to take ~30 minutes to complete and shed light on prevalent industry practices related to risering castings, shell and casting productivity, and the use/opportunity involved in recycling investment casting shells.

The results largely confirmed the research team's observations of the industry and provided metric references for the various opportunities involved in developing improved risering tools/technologies specific to investment castings, recycling shells, and improving productivity in shell (and casting) production.

Keywords: investment casting, survey, shell recycling, risering, productivity metrics, shell composition

INTRODUCTION

Investment castings are desired for their tight tolerances, smooth surfaces, and the ability to cast structurally thinner parts than sand or permanent mold casting parts or other design flexible manufacturing processes. However, the current technology process has some drawbacks relative to alternatives including a slower shell production cycle, less reuse of consumed materials in the molds/cores, and lesser defined rules for risering castings in the full array of alloys used in investment castings. Minimizing these drawbacks is likely to yield even greater interest in investment castings as the optimum solution for various military and commercial machines and building part design communities.

To capture the opportunity to overcome these drawbacks, it is helpful to understand the impacts each of these limitations has on part design, cost, quality, and lead time.

The long production lead times for the shell building part of the process result in longer delivery times, and more required space which can be a limitation on the total production of a facility.

Similarly, the inability to reuse spent shell materials requires additional cost to ship and dispose of these engineered materials plus it requires the re-order of replacement materials, which requires additional expense and resource allocation time. Fortunately, several investment casting foundries in opportune geographic locations have identified entities interested in securing these spent materials so disposal charges can be avoided. However, most investment casting foundries benefiting from this arrangement still incur shipping costs and pay for replacement materials. Hence, these additional costs result in higher casting prices.

Risering refers to the act of creating a reservoir of metal capable of taking the place of metal volumetrically shrinking in the casting cavity during cooling and solidification. Simulation inputs and risering rules have long existed and were fine-tuned in high-volume alloy and molding media combinations; however, these rules are still largely evolving in those alloy and molding media combinations with less history and scope. Examples include some of the newer Ni-base, Cr-base or even steel and aluminum-based alloys. Furthermore, as shell materials have evolved, the unfinished rules that previously existed need to be adjusted for subtle thermal conductivity and performance changes. The importance of risering and the scatter in results from these rules are exaggerated in investment casting due to the notoriously slow cooling rates caused by the preheated shell. Improper risering will yield lower quality castings, higher percentage scrap, lower yields, and accordingly a higher cost for the castings.

In response to the opportunity created by overcoming the aforementioned process limits, a co-sponsored project was devised to research options for overcoming some limitations caused by the three thrusts of shell productivity, reuse of spent ceramic, and improved risering knowledge and tools. A literature search established a list of previous efforts to improve upon these industrial thrusts.

LITERATURE REVIEW SIMULATION

Simulation is currently used for many purposes: shrink prediction, solidification rates for grain size and property prediction, for fluid flow within the mold, etc. Simple rules of thumb are not sufficient for the complex geometries of investment casting. Numerical simulation models, however, require accurate material property data and proper phenomenological models.

Xu et al. developed values for thermal properties for actual investment casting shells. These include specific heat capacity and thermal conductivity at various temperatures using the inverse method.[1] These values can be used to provide more accurate process simulations for the types of shells studied. Mathematical models are more difficult, particularly the calculation of an accurate Interfacial Heat Transfer coefficient (IHTC).

The IHTC is difficult for several reasons: First, once enough metal is solidified, it contracts and separates from the mold wall. Concurrently, the heat transfer mode changes and it becomes a step function rather than being linear. Predicting when this separation will occur has eluded researchers, in addition to the fact that in complex geometries, such as those in investment casting, this separation occurs at different times. Another reason for the difficulty is the difference in materials used from foundry to foundry and in particular the diversity with which these combinations take place. Additionally, the thicknesses of investment casting shells vary randomly (often more than 30%) which greatly affects the IHTC calculations.

For these reasons, the problem is complicated, and multiple approaches have been utilized. Stieven et al.[2] reviewed ten different optimization algorithms for the estimation of the IHTC for the specific case of aluminum-silicon alloys in permanent mold casting alone. Some examples include studies by Vossel et al.[3] and Bazhenov et al.[4] with the latter extending the work to magnesium alloys and graphite molds.

Given the complexity of the task (data collection due to temperature and the computational changes because of step functions), simplified experiments and computational approaches have been used to provide empirical approximations that generally rely on the inverse method. For example, simulation software has been used to calculate the IHTC from temperature measurements in investment casting.[5] Zhang et al.[6] used a simplified geometry in the form of a hollow steel cylinder in a furan-bonded sand mold.

Despite these limitations, casting process simulation provides excellent approximations for the investment casting process, and these approximations are used extensively. Using simulation to determine approximations is done when foundries "calibrate" the simulation system variables by adjusting raw material data and other parameters to match the results in their process. Wu et al.[7] provided an example of an investment cast titanium component design process investigating the process parameters. Determining these input parameters helped design a casting process to produce a sound, shrinkage-free casting with the requisite mechanical properties. Fang et al. provided a similar analysis for an investment cast exhaust manifold.[9]

Casting process simulation can also be used to predict some properties of castings, particularly those that depend on solidification and cooling rates such as strength from grain size. For example, properties of wear-resistant cast irons depend on the solidification rates of the as-cast microstructure.[5] Increasing cooling rates result in smaller secondary dendrite arm spacing (SDAS) in CMSX-4 Ni Superalloy[9] and da Silva et al.[10] had a similar result with the Co-28 Cr-6 Mo implant alloy. The solidification rates of these alloys can be predicted to a reasonable approximation via solidification simulation.

These mathematical methods are not limited to metal simulation. For investment casting ceramic molds Liu et al. found that Permafrost Analysis Modeling used for thawing ice, was useful in predicting deformation in ceramic shell molds at high temperatures.[11] Simulation has also been used to model single crystal solidification to predict stray grain formation.[12]

The power of process simulation to design production and treatment processes extends beyond casting flow and solidification. As examples, Tóth et al.[13] used inverse Fourier thermal analysis to predict the gas evolution from 3D printed cores. Wen et al. report using process simulation for heat treatment applications to predict final microstructures and metal properties.[14]

SHELL BUILDING

The investment casting mold is a shell that is produced by the successive deposition of ceramic layers on a pattern. The pattern is an oversized replica of the final part desired that is typically made of wax, though plastics, polyurethane foams, expanded polystyrene (EPS) foams and various 3D printed plastic patterns can also be used. The ceramic layers closest to the pattern are generally designated as "primary" coats and their main function is to resist mold-metal chemical reactions, withstand the most severe thermal conditions and produce an excellent surface finish. In some processes, some additives will be incorporated to produce equiaxed grains in the metal. The layers after the primary coats are usually designated as "backup" coats and these are primarily used to develop the structural strength in the shell mold to withstand stresses during pattern removal and pouring of the metal. Primary and secondary coats typically will have different ingredients with primary coats typically being zircon based, while back-up coats are mostly made of fused silica and/or alumino-silicates due to the expense of zircon.

Kumar and Karunakar reviewed the various relevant properties of investment casting shells while also including different pattern materials.[15] For the pattern materials, primarily wax, but also polystyrene and plastic are used. Final casting geometric properties include surface finish and dimensional accuracy, and these depend on the shell mold. Thus, the ceramic shell mold must have appropriate green and hot strengths, low thermal expansion, chemical stability, thermal shock resistance and permeability. Additionally, slurries need to be stable, and when building ceramic shells microorganisms can grow in the slurry and need to be controlled.[16] In order to improve shell properties various ingredients are added to the basic slurry system: liquid polymers to increase green strength,[17] fibers to increase green strength and permeability when the shell is fired, and fibers also help produce thicker coats when producing the shell.[18]

Chemical stability is important to avoid or minimize mold-metal reactions which can occur with resulting damage to the surface of the casting. These interactions are greater with more reactive alloys, less resistant mold materials, and higher temperatures for longer periods. Alumina-alumina shells have proven superior to alumina-silica shell systems in this regard.[19] In addition, shell systems commonly mix different ceramic materials. In another experiment, the colloidal silica binder was replaced with an aqueous polymer binder and this decreased the affected surface layer in titanium castings.[20] Yttria primary layers have been used by Lopes et al. to eliminate the mold-metal interaction in the casting of magnesium alloys.[21] Vyas et al. revealed that thicker magnesium castings promote more mold-metal reactions due to the longer time at elevated metal temperatures.[22] Kaliuzhnyi et al.[23] investigated the impact of different face coat Refractories—Al_2O_3, ZrO_2, $ZrSiO_4$ and Y_2O_3 were used as fillers for face coats. They found that a combination face coat, which contained 70% ZrO_2 + 30% Y_2O_3 slurry fillers and ZrO_2 as stucco in combination with lower metal temperatures provided by electron-beam melting provided the thinnest alpha case generation. For less reactive alloys such as stainless steel, the main concern is the thermal regime and here the choice of refractory ceramic is zircon.

Shell building is a slow process as each coat requires dipping in a slurry, coating it with stucco, and drying the slurry to activate the binder and generate the strength of the coat. Then the process is repeated until enough coats have been placed. The drying step is responsible for long processing times. Common silica sol has a long gelatinization time that leads to long production times for producing the ceramic mold.[24 25] To accelerate the process several methods have been explored: create thicker coats at each step to reduce the number of coats and thus the drying cycles; create a stronger shell with the addition of fibers, thus requiring a thinner shell and less coats; drying each coat faster; and using sodium silicate as a binder with reactants.

The thickness development of the shell is important in terms of uniformity and speed. In terms of uniformity, when shell building corners and edge regions have different structures and thicknesses when compared to flat regions.[26] With regards to speed, several methods have been tried: using larger stucco particles, and most commonly, changes were made to the slurry recipe. The first method is to increase the ratio of ceramic solids to liquids, but this comes with the disadvantage that it is difficult for the slurry to enter small crevices and holes due to the increased viscosity. It also becomes a more unstable slurry that is more difficult to maintain and manage. Another approach is to add bulking agents. For example, Pattnaik and Suttar[27] explored additions of sawdust into the slurry from 3% to 7%. They found that viscosity increased, the pH decreased but remained alkaline, the shell thickness increased with increased levels of sawdust. Permeability was highest at 5% sawdust, and while the green strength increases, the fired strength decreases with increased sawdust content.

Fibers are added to investment casting molds. Additions generally perform two duties: they increase the thickness of the slurry coat on the mold (if incorporated in the slurry) and they also strengthen the shell.

Fiber reinforcement can also be applied to plaster for investment casting. Many researchers have experimented with various fiber materials and application methods. These materials and methods include air spraying of fibers on the placed slurry, mixing nylon fibers in the slurry, fibers mixed in the stucco, etc. These generally increased the strength and permeability of the shells.[17, 28, 29,30]

The strength of the shell has been improved by the addition of alumino-silicate and glass fibers. Vyas et al. found that as the firing temperature increased, the strength effect decreased.[31] Kumar and Karunakar added acrylonitrile butadiene styrene (ABS) powder and needle coke to the shell system and reported improved permeability, higher flexural and hot tensile strengths. As the ABS powder content increased, the strength decreased. However, poorer surface finish results from the ABS powder addition in the inner shell surface.[32] Carbon fibers were added during the shell building process and resulted in ambient and hot strength increases.[33] The addition of 0.42% of 2 mm fibers resulted in peak green strength while 0.51% of 3 mm fibers maximized the fired strength. Li et al.[34] also added carbon fibers and reported that there are peak strengths to be obtained at around 0.4% fiber content, strength then decreases with increasing amounts of fiber. They also indicated that the longer fibers (4 mm vs. 2-3 mm) produce greater strength. Lü et al.[35] found that when using steel fibers, the maximum green and fired strengths were obtained in shells with 0.4% fiber content and 4 mm in fiber length. Li et al.[36] added 6 mm polypropylene fibers in the production of shells and reported that peak strength was obtained at 0.4-0.6% fiber content beyond which strength decreased.

Up to 0.2% wt. of polypropylene fibers were added to plaster investment casting molds to increase the green strength. However, larger amounts of polypropylene fibers decreased strength while fired strengths remained the same. Permeability of green specimens was unchanged, but that of fired molds increased.[37]

Li et al.[38] studied the failure mechanisms of fiber reinforcement.[38] The study found that the lowest strengthening impact was in shell building that was more susceptible to fiber pullout vs. fibers that had to actively debond from the matrix because of more successful coupling between the fiber and matrix.

One issue when adding fibers to the slurry is the tendency to clump. Feng et al. added steel fibers to the slurry to increase the strength of the shell, but the fibers were subject to clumping.[39] This clumping greatly decreases the reinforcement effectiveness of the fibers. Using ultrasonic agitation, clumping was eliminated, and increasing the power of the ultrasonic system decreased the time needed to reverse clump the fibers. Lü et al.[40] addressed the issue of fiber clumping by adding hydroxypropyl methylcellulose (HPMC) to the slurry. The addition of HPMC also increased viscosity and strength properties.

Faster drying has been used to accelerate shell mold production. This has typically involved blowing air, sometimes heated, onto the molds to promote evaporation of the binder water. Another possibility can be borrowing technology from sand casting coatings. Sand casting coatings formulated for fast drying have been investigated by Liu et al.[41] The coatings include an addition of a water reducing agent, polycarboxylic acid, which maintains the viscosity at proper levels with less water, which allows for faster drying. In addition, Liu et al. added an unspecified “quick-drying agent“ to accelerate the drying process.

In China, sodium silicate is sometimes used as a binder for investment casting. The practice consists of using sodium silicate in the slurry, stuccoing, and then reacting with ammonia by dipping. This has several adverse issues: ammonia is toxic so safety precautions are needed and when the solution becomes saturated, it must be disposed of as toxic waste. One technique under development uses microdroplets of aluminum potassium sulfate to provide better dispersion and controlled accelerator dosing, which results in superior strength properties.[42] This approach has also been done with citric acid to improve the environmental impact of the process.[43] It is important to note that both of the trials in reference were conducted on simple bar shapes, with no explanation on how it would translate to complex investment casting geometries. In addition, sodium silicate systems cannot withstand temperatures as high as those resisted by colloidal silica systems, which limit their use and/or requires additional slurry coats to make up for this limitation.

Another aspect of accelerating production of investment castings is the time from CAD model to part completion when no tooling is yet available. In this case, 3D printing has been used to accelerate the production of an investment cast article in different ways: making patterns, making core molds for mold components, making ceramic shells directly, and potentially for wax injection.

Indirect additive manufacturing is used in investment casting to produce a final product. It consists of using 3D printing to produce the patterns instead of using injected wax. The 3D printed and EPS foam patterns used in investment casting need to be removed via combustion, not traditional autoclaving. Zhao et al.[44] investigated the degradation and combustion of EPS, stereolithography (SLA), and polyurethane (PU) patterns. These materials were found to combust and can also experience pyrolysis. The EPS foam, SLA and PU foam decomposed completely at 842, 1112, & 1292F (450, 600, & 700C). However, sufficient oxygen must be present to ensure full combustion and avoid pyrolysis products remaining in the mold. The researchers also indicated that after burning at 1472F (800C) all materials had a negligible amount of ash residue.

These pattern materials, however, experience thermal expansion upon warming in the process or removing them from the mold. This often leads to mold cracking, requiring additional mold thickness to resist the stresses. For this reason, ice (frozen water) has been used as a pattern material as it contracts during melting.[45]

Choe et al. reported on the use of producing a plaster core mold using the Fused Deposition Modeling (FDM) 3D printing process to create a plaster core mold. This resulted in a much faster turnaround of the part at lower cost vs. traditional processes.[46]

Exploration of composite plaster investment casting molds was carried out by Lu et al. In their experiments, an initial layer of silica sol was placed followed by ceramic flour prior to the plaster being cast. An increase in strength was reported.[47]

SHELL RECLAMATION

Currently, spent ceramic from shell molds is usually disposed of in landfills. In some limited instances, the material may be applied as a beneficial reuse alternative, for instance, as fill in construction projects. The maximum economic impact would be to reuse the material as originally intended. The ceramic aggregates, if not mechanically degraded, have the potential to be reused as originally intended. Laboratory experiments on these have been performed that indicate that this may be feasible.[48]

The shell constituent ceramics include different minerals: primarily fused silica, zircon, and alumino-silicates in both a flour and stucco (sand grain size) particle size. To reuse these materials, it is necessary to break them up from the spent shell and separate them into the initial material streams. To break these materials to size, ball milling was used in previous experiments. Similarly, separation by size was done using screens. However, separation by mineral composition was not attempted but can be considered between the zircon used in primary coats and the alumino-silicates and fused silica stuccoes used in backup coats due to the difference in densities of the materials. Flour separation would be much more difficult due to the particle sizes involved.

Whitehouse et al.[49] conducted tests using various formulations of slurry and stucco for the primary coats. It was concluded that the tested stucco could be used if the prime slurry viscosity were optimized. This hints at the possibility of being able to modify slurry practice to accommodate the use of reclaimed stucco, if needed.

Some equations relate to the comminution of ceramics into powders.[50] However, the equations relate to homogeneous materials to be fully converted to powder, not to break up non-homogeneous materials into their original discrete components.

Zircon is used as either the prime slurry and/or stucco in most investment casting foundries. Zircon is an excellent refractory for use in investment casting due to its round shape, refractoriness, low reactivity with molten metals, and a relatively low thermal expansion. The high refractoriness allows the use of finer particles that result in improved surface finish where the mold contacts the molten metal.[51] The fluctuation in zircon availability, along with its increasing price due to strong market demand, means that many investment casting facilities are currently looking for alternative materials. Zircon is expensive and suffers from cyclical shortages.[52] Most zircon is mined outside of the U.S. as well creating a strategic supply issue. Another approach, which is part of the scope of this project, is to reclaim and reuse this zircon.

Multiple reclamation efforts have been made to reclaim zircon from sand molds and investment casting molds. Zircon reclamation has been considered previously. One effort describes the possibility of concentrating zircon-rich fragments and then chemically leaching the zircon out. However, difficulties in obtaining the zircon-rich fragments and potential contamination of the slurries with leachate residuals were cited as significant difficulties.[53] Generally, reclamation efforts have proven too difficult to perform as they relied on chemical methods and scraping the areas of the mold where the zircon is present. Smith[54] proposed a method that breaks down the shell into the original aggregates and then separates them. Some work has been done in the use of reclamation of the aggregates but without separating the zircon.[55]

In two papers, Holtzer et al.[56,57] describe the breakdown and reuse of investment casting shell material. They report that the rheological properties and green strength of the test molds made with reclaimed flour to be better than those made with virgin materials, however, the hot strength suffered. They did indicate that use of the reclaimed stucco improved properties. Howmet reported practicing reclamation by crushing and air classification. They worked with an alumina system. Impure fractions of initial components (80-85% purity) were reported.[58]
The proposed method of ceramic breakdown and reclamation has been performed on a laboratory scale.[48] The fused silica stucco broke down to less than the desired size and was thus not reusable while alumino silicates did maintain integrity and it is speculated that zircon will too. Because shells for nonferrous alloys are typically made of zircon and alumino-silicates, it is anticipated that it will be possible to recover most of the stucco with the possibility of separating the bulk of the zircon stucco with density separation methods.[48]
The purity of raw materials has been identified as critical in maintaining high-temperature flexural strength. Sodium-based alumino silicate phases caused the shell to weaken at temperatures over 1832F (1000C). Thus, avoiding cross-contamination is essential in any reclamation effort.[59] Sandt et al.[60] developed causal graphical models to ensure that the green sand reclaimed was of adequate quality. These models may be used to ensure the quality of the reclaimed ceramics.

EXPERIMENTAL PROCEDURE

An online survey was conducted to establish baseline metrics for the current practices of the domestic investment casting industry. The online Survey Monkey® platform was used to transact the survey with the questions programmed with logic so the number of questions to be answered varied between 24 and 26 based on the answers provided to each question. Most of the questions were multiple choice but with the option to select "other" if selections other than the preselected multiple-choice options were possible. When "other" was selected, an open field was made available for respondents to type in an answer. Three questions were open-text fields for typed-only responses.

The survey was preliminarily drafted by the project team and refined by the AFS Investment Casting Committee for full applicability to the industry. The survey was sent to nearly 500 verified email addresses from active investment casting foundries incorporated in the USA. Although a few dozen locations had the survey sent to multiple employees, the survey requested that members coordinate internally to combine responses into a single survey.

A total of 37 surveys were submitted from February 29, 2024 until mid-May 2024. Although several respondents exercised the option to remain anonymous, a glance at the survey suggests that only a single operation submitted a duplicate location survey suggesting 36 unique operations were surveyed. Survey Monkey® allows the user to export the results as both tables and bar charts in the form of a .pdf to facilitate analysis. When helpful, Adobe Acrobat Reader was used to convert the .pdf files into .xlsx files for sorting and additional viewing options.

RESULTS

Next, the survey questions will be presented with the results and interpretations of those results. Note that in some instances the totals will add up to more than 100, as some foundries will meet more than one category, such as pouring multiple alloy families.

Q1. What alloys do you pour? (select all that apply)

A graphical illustration of question 1 responses appears in Figure 1. The rank order of alloys surveyed was steel, aluminum Ni-Base, Cu-base, cast iron, Cr-base, and single respondents reported pouring Mg- and Ti-base, respectively.

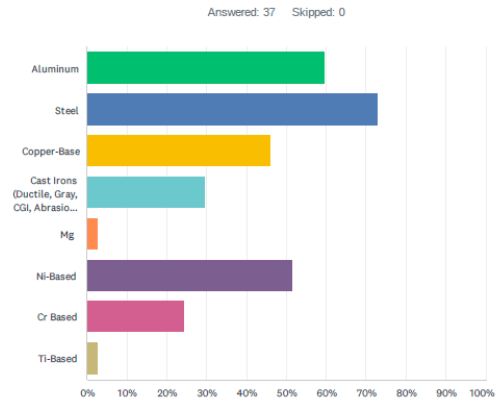

Figure 1. Responses to Question 1 on alloys poured (select all that apply).

Q2. Weight range by casting weight?

A graphical illustration of question 2 responses appears in Figure 2. Slightly over 50% of the respondents reported exclusively pouring castings less than 100 lbs. (45 kgs) while slightly under 50% of respondents reported pouring castings weighing both less and more than 100 lbs. (45 kgs). Only one respondent reported exclusively pouring castings weighing over 100 lbs. (45 kgs).

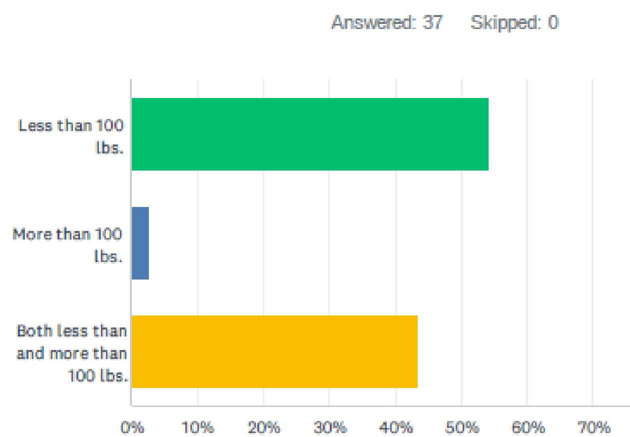

Figure 2. Responses to Question 2 on reported weight ranges by casting weights in ranges of less than 100 lbs. (45kgs), more than 100 lbs. (45 kgs), or both less and more than 100 lbs. (45 kgs).

Q3. Overall max slurry tank diameter size?

A graphical illustration of question 3 responses appears in Figure 3. Contrary to expectations, the slurry tanks were larger than anticipated with only two respondents (5%) reporting less than 20 inches (51 cm) in diameter, and a healthy 68% being larger than 30 inches (76 cm) in diameter, with the remaining slurry tank diameters being between 20 and 30 inches (51 cm and 76 cm).

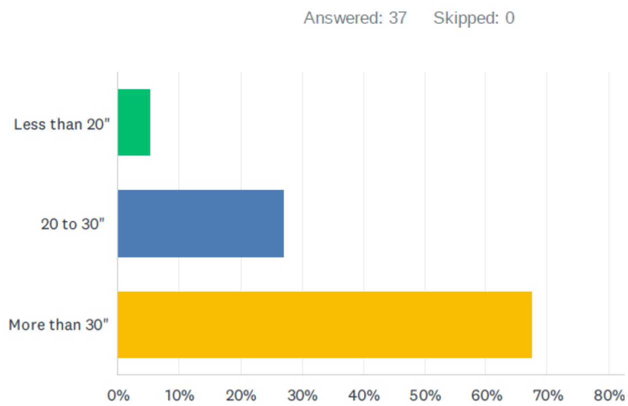

Figure 3. Question 3 responses for overall max. slurry tank diameter sizes.

Q4. Markets Served? (select all that apply)

A graphical illustration of question 4 responses appears in Figure 4. As expected, the responses exceeded 60% in all three of the listed markets: defense, commercial and aerospace.

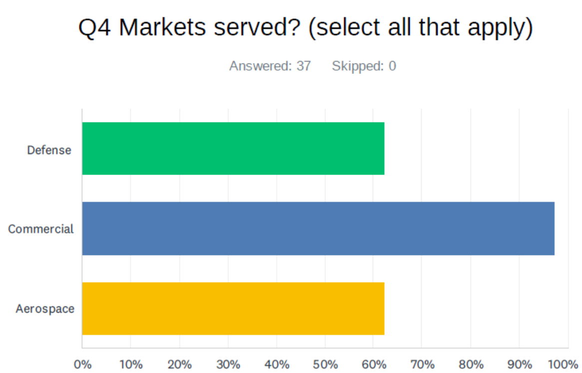

Figure 4. Question 4 responses to markets served (select all that apply).

Q5. Typical mold/shop yield (casting weight/poured weight)?

A graphical illustration of question 5 responses appears in Figure 5. The typical mold/shop yield was very uniformly distributed with all five categories receiving a nearly equal distribution between 16 and 24%. This matches well with the authors' experiential observations. There is likely some alloy and part size bias to each of these categories, but a full statistical analysis is outside the scope of this project. The results do reinforce the need for better risering knowledge and tools.

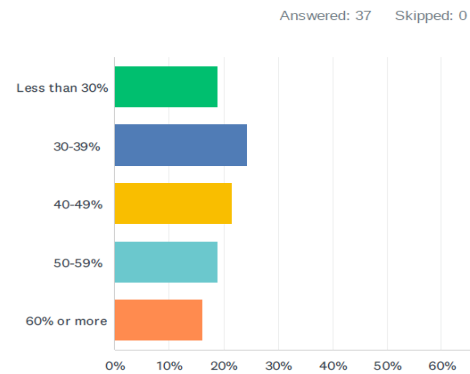

Figure 5. Responses to Question 5 for typical mold/shop yield (casting weight/poured weight).

Q6. Do you use a riser sizing/calculator tool?

A graphical illustration of question 6 responses appears in Figure 6. Responses showed that 73% indicated that no riser sizing/calculator tool is used, which supports the need for a publicly/commercially available tool.

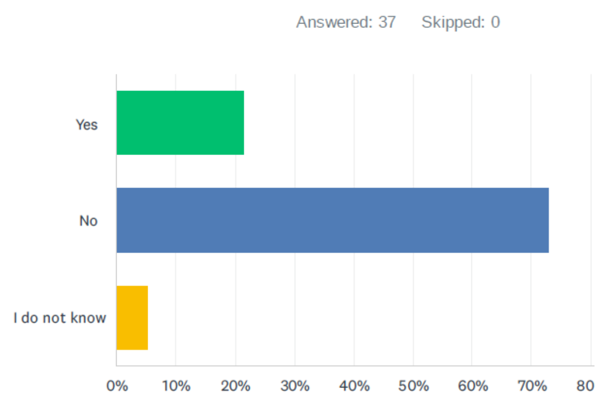

Figure 6. Responses to Question 6, Do you use a riser sizing/calculator tool?

Q7. Do you use process simulation software?

A graphical illustration of question 7 responses appears in Figure 7. A little more than half (57%) of the responses indicate process simulation software is used for casting layout. Conversely, less than half (47%) do not use process simulation software. One might infer that no more than eight of the respondents are likely using a solidification module since only eight respondents reported using a riser sizing/calculator tool in the preceding question 6. However, given the answers to questions six and seven, it is more likely investment casters are not using separate risers in the traditional sense and are using tools to meet the casting solidification feeding function that risering normally addresses. This may be a difference in practice and terminology as much of the casting solidification feeding in investment casting is done through the gating system.

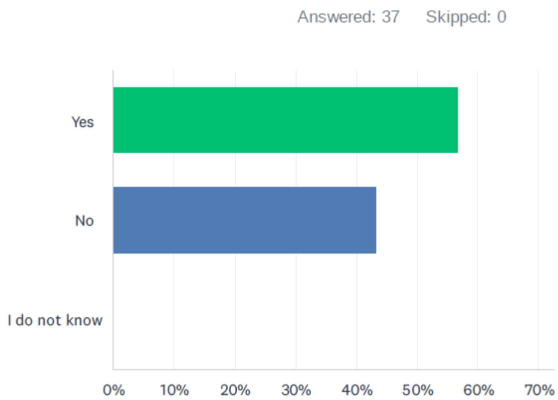

Figure 7. Question 7 response to "Do you use process simulation software?"

Q8. If you answered yes to the previous question, check all that apply.

A graphical illustration of question 8 responses appears in Figure 8. Unfortunately, only 6 of the 21 respondents answered the follow-up question about the purpose of the process simulation software. The question was likely flawed in design as it did not permit an answer of "other" and permit an open field for a different answer. All six responses received were identified using process simulation software to assist with risers and/or/feeding needs.

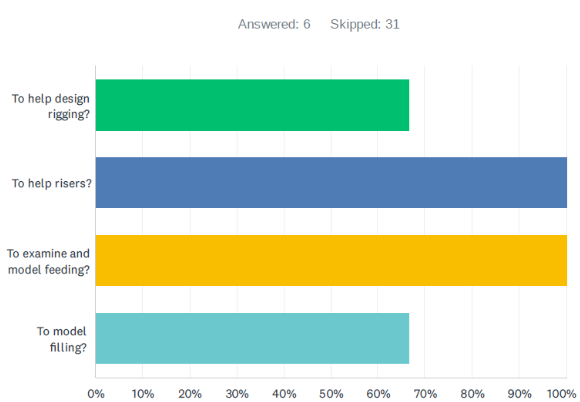

Figure 8. If you use process simulation software, check all the reasons listed that apply, Question 8 response.

Q9. Plantwide % scrap due to shrinkage-related defects (like number of castings scrapped/repaired vs. produced/shipped)?

A graphical illustration of question 9 responses appears in Figure 9. A total of 28% reported having 5% or more scrap due to shrinkage-related defects. These operations are likely those that could see immediate benefit from a riser sizing/calculator tool. Interestingly, two respondents appeared to disengage from the survey here as all future questions have at least two respondents reporting as having skipped the questions.

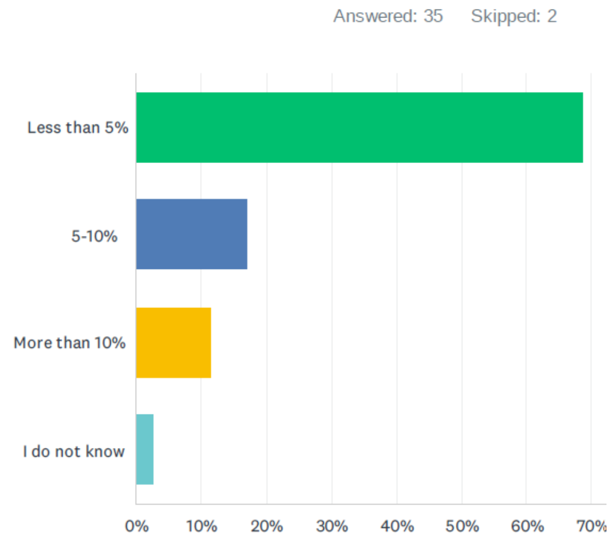

Figure 9. Question 9 responses to plantwide % scrap due to shrinkage-related defects.

Q10. Plantwide % rework (weld repair) due to shrinkage-related defects (like number of castings scrapped/repaired vs. produced/shipped)?

A graphical illustration of question 10 responses appears in Figure 10. Building upon question 9, this one asked for the percentage of castings that were salvageable through rework due to risering issues rather than non-salvageable. A total of 37% cited a significant need (5% or higher) to re-work castings. There is likely an alloy bias on this data, but again quantitatively assessing such a bias is outside the scope of this project. It is important to note that the questions asked about shrinkage defects exclusively, thus excluding scrap and rework for other reasons.

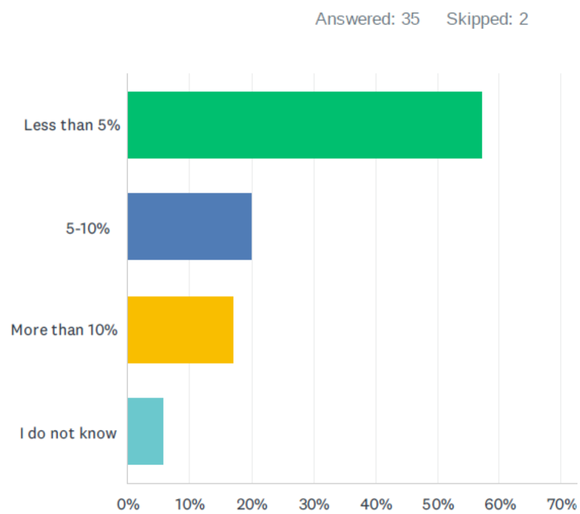

Figure 10. Question 10 responses to plantwide % rework (weld repair) due to shrinkage-related defects.

Q11. Average annual tonnage of ceramic shell being dumped in the landfill or hauled away?

A graphical illustration of question 11 responses appears in Figure 11. Disturbingly, nearly 50% of the responses report not knowing the tonnage of ceramic shell being dumped in the landfill or hauled away. Potential reasons may be mixing of refuse (shell material plus slag, for instance) or this information is just not collected. Perhaps, this is why there has been historically less attention being focused on the opportunity to recycle shells.

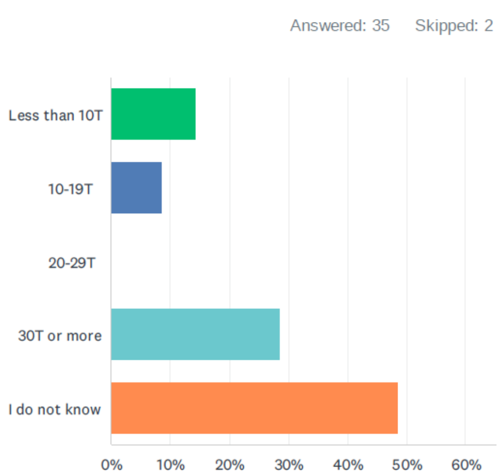

Figure 11. Response to question 11 that referred to the average annual tonnage of ceramic shell being dumped in the landfill or hauled away.

Q12. Do you recycle used shells in your process?

A graphical illustration of question 12 responses appears in Figure 12. True to expectation, most responses reported that shell materials are not being recycled in their process. Two of the four respondents reported yes to recycling shell materials reported anonymously. The two respondents providing contact information will be approached for further insight.

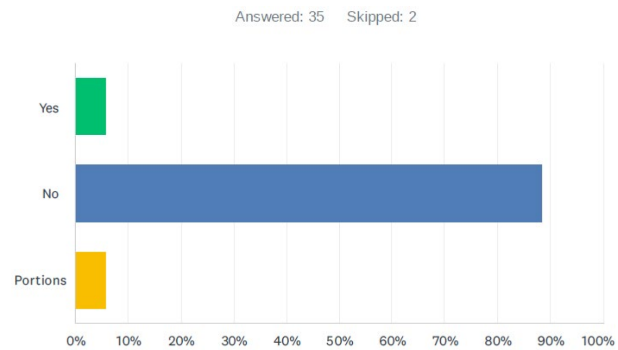

Figure 12. Question 12 responses to "Do you recycle used shells in your process?"

Q13. If you recycle used shells, what % of the shells are recycled?

A graphical illustration of question 13 responses appears in Figure 13. This question appeared if respondents responded "yes" or "portions" to question 12. As expected, all four respondents remaining from the previous question responded and only one of the responses reported recycling as high as 25% of the materials.

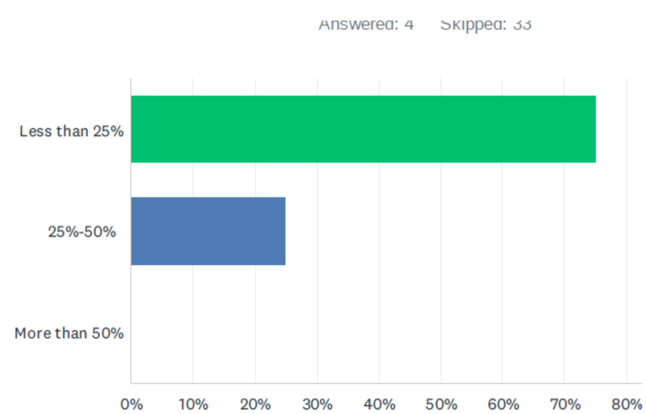

Figure 13. If you recycle used shells, what % of the shells are recycled?

Q14. What is your typical lead time to prepare shells for the reorder products with existing tools, the clock time starting with patternmaking until shell completion?

A graphical illustration of question 14 responses appears in Figure 14. Very disappointingly, only 4 of the 37 respondents responded on the lead time of the shell process. The four respondents are suspected best in class as they reported in the two lowest time length options provided. In hindsight, an answer option of "I don't know" or mandating would have been appropriate in the question design, but during inception of the question structure, it was thought that some respondents might not know the answer and force false information.

Figure 14. What is your typical lead time to prepare shells for the reorder products with existing tools, the clock time starting with patternmaking until shell completion?

Q15. What is your typical lead time for new products, the clock time starting with building a new wax injection die until finished casting (if a breakdown is provided will be better – tooling related lead time, patternmaking and dewaxing; shell drying, pouring and finishing including rework)?

A graphical illustration of question 15 responses appears in Figure 15. Answers here ranged from less than three to twelve months. Additively Manufactured (AM) patterns could likely lower this, but volume requirements often make AM tooling non-practical economically. The AFS Investment Casting Committee is working on a separate project to identify a solution for this possible opportunity.

Q16. What is your typical lead time for the reorder products with existing tools, the clock time starting with patternmaking until the finished casting (if a breakdown is provided, it will be better – patternmaking and dewaxing; shell drying, pouring and finishing including rework)?

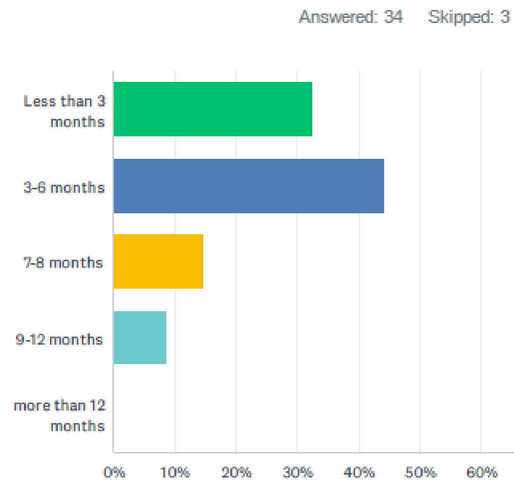

Figure 15. What is your typical lead time for new products, the clock time starting with building a new wax injection die until finished casting?

A graphical illustration of question 16 responses appears in Figure 16. Answers to lead time with existing tooling encompassed all answer options, although over 50% of the respondents can deliver parts in 11 weeks or less with nearly half of those capable of doing so in 8 weeks or less. In questions 15 and 16, no separation was made between commercial and aerospace products. This is significant due to the typically more extensive processes after production for aerospace products such as dye penetrant and others.

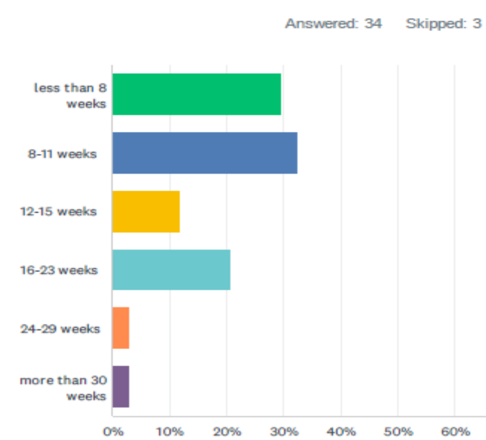

Figure 16. What is your typical lead time for the reorder products with existing tools, the clock time starting with patternmaking until the finished casting including rework?

Q17.What is the % of projects using 3D-printed wax-like patterns (SLA, PMMA, PLC, etc.)?

A graphical illustration of question 17 responses appears in Figure 17. The matriculation of 3D-printed patterns as opportunistic replacements for wax slurry precursors is happening; although only 30% of the respondents are using substantially at a threshold amount of more than 5% of all projects.

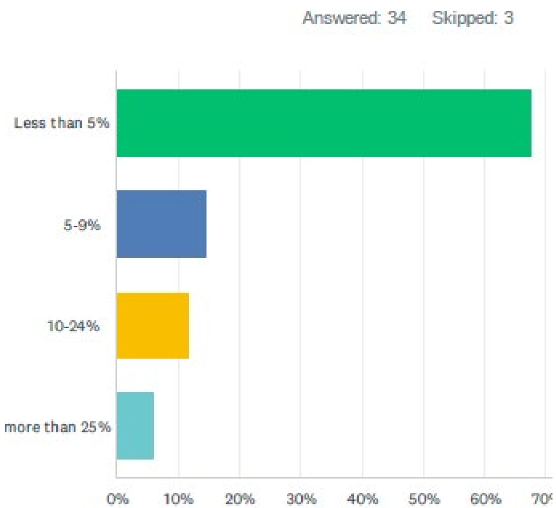

Figure 17. Responses to question 17, What is the % of projects using 3D-printed wax-like patterns (SLA, PMMA, PLC, etc.)?

Q18. What is/are the purpose(s) of using 3D-printed wax-like patterns? (select all that apply).

A graphical illustration of question 18 responses appears in Figure 18. As anticipated, 3D-printed wax-like patterns are used commonly for prototyping, low-volume production, and for pre-trial materials while production tooling is being built. Three respondents selected "other" as the reason for using 3D printed wax-like patterns and their listed reasons were: N/A, geometry of part is not compatible with the requirements of permanent mold, and 3D print patterns save in rubber mold costs and storage or disposal for one-off pieces.

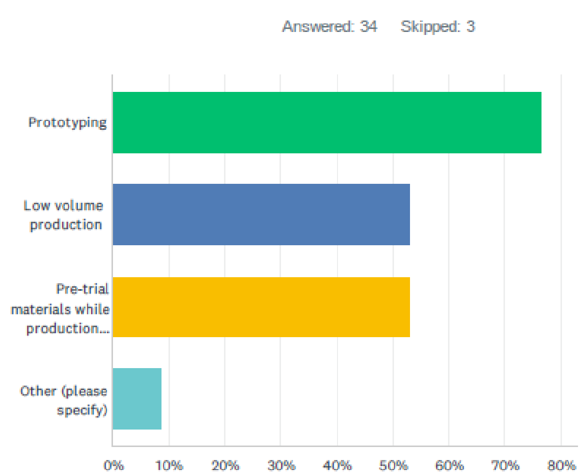

Figure 18. Question 18, What is/are the purpose(s) of using 3D-printed wax-like patterns? (select all that apply)

Q19. What stucco materials do you use? Select all that apply for primary through seal coats.

A graphical illustration of question 19 responses appears in Figure 19. Zircon and fused silica each garnered a response in over 70% of the surveys. Alumino silicate (32%) and alumina (18%) were significantly lower. Two respondents selected "other" and provided the following responses: none and proprietary, chose not to disclose.

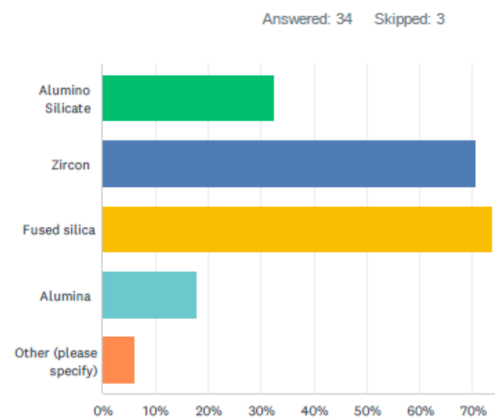

Figure 19. Question 19 response to, What stucco materials do you use? Select all that apply for primary through seal coats.

Q20. If alumino silicate, what grade?

A graphical illustration of question 20 responses appears in Figure 20. Of the eleven respondents selecting alumino-silicate as their stucco material, six advised that they use 47% alumina while the other 5 selected 60% alumina. No one reported using higher than 60% alumina content in its alumina silicate stucco.

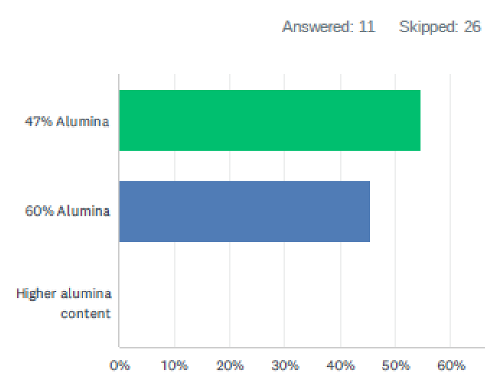

Figure 20. Response to Question 20, If alumino silicate, what grade?

Q21. What flour materials do you use? Select all that apply for primary through seal coats.

A graphical illustration of question 21 responses appears in Figure 21. The results of the flour materials inquiry were similar to the stucco material survey in that zircon and fused silica represented a majority of the responses. Alumino-silicate and cobalt aluminate showed up on nine and seven of the respective surveys. Four surveys selected "other" as a primary seal coat and those other materials responses follow: mullite (an alumino silicate), none, alumina, and proprietary, chose not to disclose.

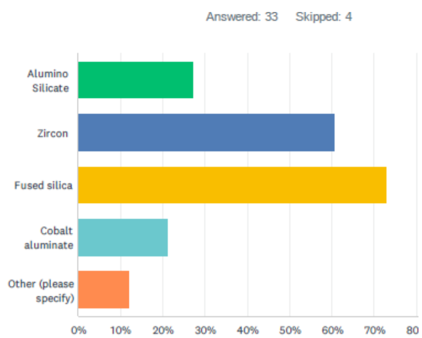

Figure 21. Question 21 response to, what flour materials do you use? Select all that apply for primary through seal coats.

Q22. What mesh size range is your stucco? Include primary through seal coats. (Please indicate the largest mesh size and smallest mesh size for your materials)

A graphical illustration of question 22 responses appears in Figure 22. The responses to the mesh size ranges in the stucco varied greatly with several respondents being unaware of their respective mesh sizes. The various ranges establish the difficulty in recycling spent stucco to a matched mesh size in the industry.

Largest	Smallest
16/30	120
Unknown	Unknown
?	?
140	200
30	400
50	120
?	?
30	100
Unsure	Unsure
80	200
Prop.	Prop.
30-50	50-100
50	200
Do not know	Do not know
20	Zircon
30	120
-30 to +50	-5 to +100
10/30	-400
22	105
Proprietary- choose not to report.	Proprietary- choose not to report.
100	120
0	0
Not sure	
22	60
Remet RG-3	Remet RG-1
Not sure	Not sure

Figure 22. What mesh size range is your stucco?

Q23. What is your average plantwide shell drying time?

A graphical illustration of question 23 responses appears in Figure 23. The responses to average plantwide shell drying times matched expectations with 72 hours being a logical index point. Three more respondents reported under 72 hours than those who reported over 72 hours.

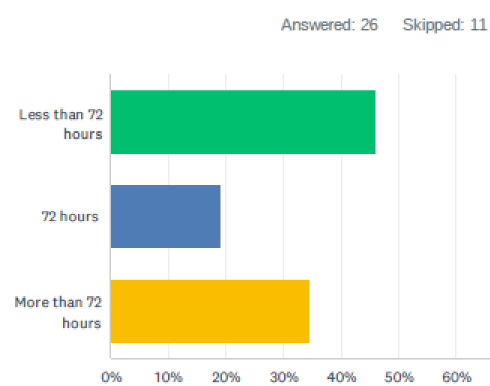

Figure 23. What is your average plantwide shell drying time?

Q24. What is the largest mesh size in your flour?

A graphical illustration of question 24 responses appears in Figure 24. Meshes 120, 140, and 200 appear in multiple responses and appear to be pseudo-industry standards, particularly the two latter sizes.

Largest Mesh Size
-270
Unknown
?
140
140
120
?
200
Unsure
80
Prop
200
200
Do not know
90
-120
?
NA -Use SuspendaSlurry®
200
Proprietary- choose not to report.
100
0
Not sure
140
Remet RP-1
Not sure

Figure 24. What is your largest flour mesh size?

The final two questions were optional and asked respondents to provide name/contact information and inquire about their interest in joining the project steering committee. Seventeen of the respondents did provide contact information and will be approached to participate.

CONCLUSIONS

Several conclusions were drawn from the results of this survey and include:

1. Industry-wide yield is a mixed bag and seemingly supports the need for improved risering tools in alloys and molding criteria where they do not exist.
2. High-scrap and or re-work due to shrinkage-related defects are not systemic in the industry but compromise portions of the industry; a portion that hopefully can be assisted to achieve improvement.
3. Industry lead times are quite scattered regardless of whether foundries need to create new tooling or not. Interestingly, a survey question prompting respondents to report on the time specific to shell manufacturing received very few responses suggesting that it is possibly unknown or too volatile to confidently determine.
4. The 3D-printed wax-like patterns are slowly proliferating within industry. The predominant reasons for their use are prototyping, low-volume toolingless production, or as an interim solution while awaiting production tooling. Nearly 70% of respondents report using 3D wax-like patterns, less than 5% hinting that there may be a need for further research and technology transfer before comprehensive industry adoption.
5. As expected, industrial shell recycling remains in its infancy per the survey responses. A literature search confirmed efforts are in place globally to overcome the remaining hurdles for implementation. Zircon and fused silica remain the biggest opportunities due to largest use, followed by alumino-silicates, alumina, and cobalt-aluminate. A wide spectrum of mesh size requirements in the industry will require solutions tailorable to each facility's needs.

SUMMARY

A survey of various practices within the domestic investment casting industry was undertaken and seemingly confirmed opportunities to improve risering techniques, recycle shell materials, and increase/stabilize the productivity of shell production within the industry.

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To improve readability of the manuscript, the author(s) used the following AI-Technology/Tools: Grammarly. The specific content was used non-generatively to edit the document for grammar, punctuation, and improved sentence structure. After using this AI tool, the authors reviewed and edited the manuscript content and take full responsibility for the content of this manuscript.

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