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The Investment Casting Conversion Process: An Industry Consensus

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ABSTRACT

Newcomers to the investment casting market, specifically buyers and designers, face challenges in navigating a new territory of terminology, value elements, and market forces. The purchasing and design methods that have worked previously might suddenly have unexpected shortcomings. Also, it can be difficult to make decisions when your contact with the industry is limited, and a small error can result in a project being stalled or never realizing its full potential.

This paper aims to convey practical information about the procurement and design of investment castings by demonstrating quantitatively the consensus among industry veterans about these topics. A broad group of casting professionals has been empaneled to supply input, including:

- Investment casting engineers and foundry managers
- Experienced designers and buyers of investment castings

This is not a paper about negotiation or design of parts (though it has elements of those useful things). Rather, it is a practical paper about avoiding common pitfalls as a manufacturer brings a new casting to market. It also contains a condensed Appendix for ready reference.

Keywords: fabrication, conversion, investment casting, design, purchasing, optimization, lightweighting

INTRODUCTION

Like any industry, the Investment Casting industry features repeat customers. These customers develop a rapport with the individual investment foundries in their supply base. Both parties can prosper with the development of relationships featuring excellent communication and common understanding of what is possible.

When a foundry seeks to penetrate new markets with new customers, such common ground might not exist. At the same time, it is a fact that the Investment Casting industry can generate value and sales by replacing fabrications and forgings with castings. This entails approaching designers and buyers with information about investment castings. This means an educational effort. Fortunately, informational resources are plentiful if one seeks them out.

Even so, information transfer is only part of the challenge to those seeking to sell casting conversions. Those who design fabrications and who buy such components may have zero familiarity with any sort of casting process. Even when it is explained well, there are some all-new hurdles that crop up in the Purchasing cycle.

The potential customer realizes that a whole new language and skill set are required. For example, they likely have not considered casting tooling costs, ever. Also, it is common that only one foundry is making the value proposition (let us help you convert fabrication to casting so you can save costs), so a buyer might suddenly be facing a “sole source” situation.

This combination of factors can lead to skepticism and pre-emptive cancellation of conversion projects; it is just too much for a newcomer to the investment casting process.

This paper aims to address some technical and human challenges inherent in the process of selling investment casting conversions to designers and buyers of fabrications and forgings. The author empaneled respected members of the Investment Casting industry to validate points being made. He also included on the panel those who are engineers, product managers, and buyers with experience in the design and purchasing of investment castings. Both sides of the Purchasing transaction were represented to illustrate a consensus on these topics.

These panelists were presented with a series of statements about various aspects of investment casting design, sourcing, application, and manufacture. The panelists voted on these individual statements, and the voting numbers are presented in this paper. They were asked to vote on scale of 1-10, on the ACCURACY of the statements: *Is the statement true as it is written?* They were then asked to vote again on the RELEVANCE of the statement: *Does this statement matter to the investment casting conversion process? If I am designing/buying an investment casting, does this topic have a bearing on my work?*

Those scores were then tabulated as an average score, showing an industry consensus on the topic. For example, the numbers shown in the table below show the average response, on a scale of 1-10, of the responding panelists, on the Accuracy and Relevance of the statements shown below, about Investment Casting materials (more on this topic later):

	Accuracy?	Relevance?
Investment Cast material is not necessarily the fabrication material	9.92	9.85
Investment Cast material flexibility = design options	9.85	9.92

Thirteen out of fourteen panelists gave scores.

Lastly, panelists were encouraged to offer comments to emphasize points that may need further explanation. The individual attributions of these comments are confidential.

This paper provides a quantitative measure of the truthfulness and applicability of various statements and shows that an industry consensus exists across both sides of the sales/purchasing table, while at the same time not confining the panelists to only ideas that the author has presented. Such a consensus can ease the transition for newcomers to investment castings. This paper and presentation will be available to ICI membership.

INVESTMENT CASTINGS VS FORGINGS AND WELDMENTS

A casting might appear more expensive than a weldment at first. But a buyer has to weigh the total cost of the product, including reduced machining, reduced weight, etc. There are applications, such as in Figure 1, where using an investment casting will reduce:

- Overall cost
- Weight
- No. of SKUs (part numbers)
- Reduced assembly costs

Also, though it is harder to quantify, the investment casting will also usually be more elegant and aesthetically pleasing than a fabrication. Investment castings can allow you to cast lettering and part numbers readily and attractively on the actual part (Figures 2 and 3).

There are also applications where an investment casting is not a fit. The foundry will tell you so.

The most important factor is getting an experienced designer to consider casting as a design option as early in the process as possible to avoid unforeseen roadblocks that could stall the process.

The most common barrier to the weldment-to-casting conversion process is the tooling cost. That said, tooling cost is not what it used to be due to advances in additive manufacturing technology (more on this later), and it is a non-recurring cost.

Lastly, there is no need to be apprehensive about your options. As a buyer/designer, you likely have multiple domestic producers available in terms of your casting supply chain.

	Accuracy?	Relevance?
You can often cut significant costs going from fabrication/forging to casting.	9.15	9.31
Tooling cost, a traditional barrier, is not what it used to be.	9.31	9.46
There are multiple domestic Investment Casting foundries.	9.77	9.77

Panel Comments on Investment Castings vs Forgings and Fabrications:

- *Beyond the tooling costs, qualification costs need to be considered for existing designs (so earlier is better).*
- *Site visits at the foundry can inspire the beginning designer by showing other casting designs.*
- *Once the wax die is certified, you can count on the reliability of those dimensions for decades as compared to machining and forging.*
- *It is very part-specific, regarding how much money you can save.*
- *Your choices as a buyer will vary depending on alloy and size envelope especially.*
- *In my experience, the greatest barrier in going from a weldment to a casting is getting customer engineering design and support.*
- *In aerospace, you do not traditionally convert forgings to castings. You are more likely to convert a part that was hogged out of barstock.*
- *There are more tooling options today.*
- *There are more tooling options available today. Printed tooling for cores, printed cores, etc.*

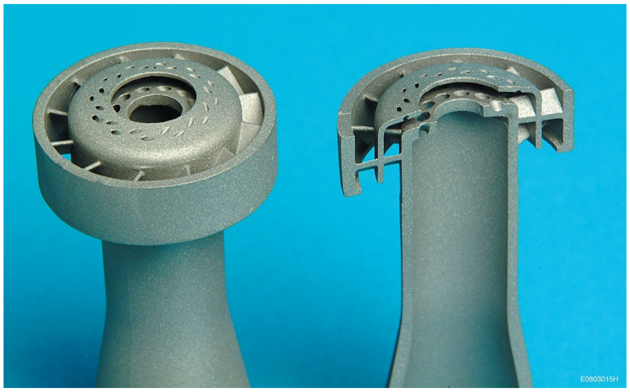

Figure 1. Swirler for gas turbine engine is a small part which replaced 27-piece fabrication.[1]

Figure 2. An investment casting showing cast finish and as-cast lettering raised in a recessed area. (Artwork courtesy of Uni-Cast, LLC.)

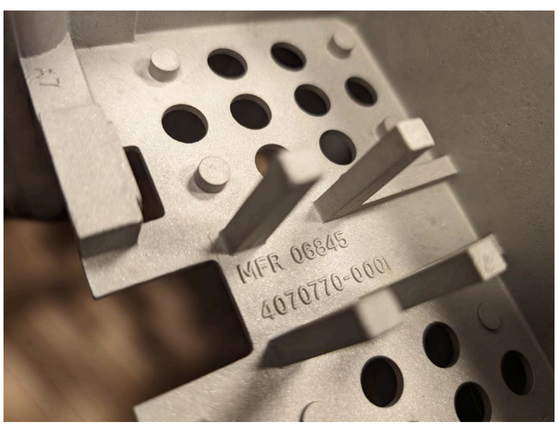

Figure 3. An investment casting showing cast finish and as-cast lettering raised. (Artwork courtesy of Uni-Cast, LLC.)

WHAT TO INCLUDE IN AN RFQ FOR AN INVESTMENT CAST COMPONENT

If a decision has been made to produce a part as an investment casting, then at some point a Request for Quote (RFQ) will likely be generated to go to potential sources. As a buyer/designer, you likely have multiple domestic options in terms of your casting supply chain.

The buyer will want meaningful quotes to be submitted. Below are some guidelines for what to include in an RFQ for an investment cast component:

Drawings, including part number, part name, and revision level.

- Casting drawing in .pdf format,
- If machining is required, there should be a machined casting drawing.
- It would be beneficial to indicate any critical areas on the casting, including preferred or designated machining locating areas.
- Ideally, model files in the appropriate format will be provided.

Material type

- RFQ should list the type and grade of material required (should be on drawing, too).

Prototype or production?

- This is important information, as it lets the foundry know whether to quote prototype or production tooling as well as whether assistance with rapid prototyping is required.

Volumes

- Estimated annual usage (EAU)
- Lot sizes and frequencies
- If prototypes are required, the volume of prototype pieces that are required.

Part Weight

- Accurate part weight is critical and often misstated, even in the age of digital models.
- This can have a significant impact on pricing.

Value-added operations

- Any paint/powder/etc.
- Machining
- Heat Treatment

Certifications

- Any material certs or special testing
- NDT requirements, including X-ray
- Which standards are required as part of the certification?

Timing

- Time requirement to return the quote (outside tooling will add time to delivery of quote)
- Sample start date.
- Production start date.

Panel Comments on What to Include in an RFQ:

- *At the prototype stage of the process, it is very important to glean manufacturability input from the foundry for your design. The prototype cost might not reflect the final cost, in either direction.*
- *3D CAD models are critical. This is the 21st century. You need models to understand the castability of the part and the complexity of the tooling that will be needed.*
- *Foundries do a lot of quotes, and land comparatively few jobs. Does it even make sense to send this RFQ to this shop? Are they a fit? Or am I wasting everyone's time?*
- *Models are almost mandatory. If a part is being re-sourced and there is no model, we will commonly 3D scan the existing part anyway.*
- *It is good practice for the vendor to reply to your RFQ the same day to at least acknowledge that you received the RFQ.*
- *There needs to be a fit between the customer and the foundry in terms of equipment and other factors.*
- *Be as straightforward as possible on EAU.*
- *Quotes take time, often several hours. "Fishing" quotes are easy to detect and are not taken seriously.*
- *After we get the RFQ, we will commonly have a conference call with recommendations and exceptions before submitting the quote.*
- *Casting drawings should specify surface condition requirements by surface; they should indicate allowances for gates, etc.*
- *If the part has export controls, this needs to be noted.*
- *Often the casting design may call for a simple and inexpensive part but overdoing the notes and restrictions can drive up the overall cost significantly.*
- *In general, the issue with RFQs is that they are not specific enough. They are stated in a way that backs the supplier into a corner, and the supplier will no-quote.*
- *Any APQP and PPAP requirements should be presented right up front.*

INVESTMENT CASTING TOOLING

With a few exceptions, investment casting tooling belongs to the customer. Investment casting tooling includes more than the die (Figure 4) that produces the wax pattern. There are other types of tooling, such as straightening fixtures (Figure 5), machining fixtures, core tooling, etc. These items can vary, and some can rise in complexity and cost to rival the main die.

When getting a quote on tooling, your tooling costs, either up front or amortized, will vary from foundry to foundry depending on:

- Program requirements
- Quantities
- Lot sizes
- Complexity
- Other shop equipment (molding machines, robots, etc.)
- Ancillary processes (machining jigs, etc.)

For example, one foundry might quote a straightening fixture immediately, thinking it a necessity. Another might exclude such an item, thinking it unneeded. When comparing quotes, these line items should be noted.

Also, if a buyer sees a massive difference (multiples) in tooling prices between two sources, then this is worth an inquiry. It is possible something has been overlooked or misunderstood.

Lastly, rework, maintenance, and gating of tooling can be costly. This should be discussed openly.

	Accuracy?	Relevance?
Investment Casting tooling can include many pieces	9.92	9.92
Multiple factors drive tooling cost	9.92	9.92
Large differences in tooling quotes warrant a close look	9.92	9.92

Panel Comments on Tooling:

- *Not all tooling quotes are the same. One shop might include a CMM fixture, etc.*
- *There is a lot of benefit to having a bona-fide tool room in the foundry; there is a synergy to the collaboration between the tool room, the wax room, the shell room, and the melt shop.*
- *Unusually cheap tooling quotes warrant exploration. Why so cheap? Did they omit something? Chances are that when production starts there will be another tool required and another bill.*
- *Compression straightening can be 60% of the cost of a tooling package.*
- *Maybe the less expensive tool is made of a material suited to low volume.*
- *All tooling belonging to the foundry should be hard-tagged and photographed, indicating its ownership for asset tracking purposes.*
- *The need for a straightening fixture can be 60% of the tooling cost. If the piece cost is low, this is justified to reduce labor.*
- *You can minimize straightening issues and tooling costs with casting design and casting process optimization using numerical simulation tools.*

- *The wax die can be tool steel or aluminum, for example. We could go on all day on the differences in tools.*
- *The use of external solubles instead of complex finished die tooling can make a huge difference in cycle time and finished cost.*
- *Tooling cost is heavily influenced by product volume. You might need a more expensive die for higher volume. More automated tools cost more. Piece price and tool price go together.*
- *Before building a tool, do a process simulation to optimize the gating, etc.*
- *Foundry quotes tend to neglect including gages even when the drawing indicates that a feature is to be gaged.*
- *Canadian/US exchange rate impacts tooling/casting quotes a great deal. At the time of this writing, the difference is 30%.*
- *A multi-cavity die might be more expensive but would be suited to high volume parts. This might be worth it to offset higher piece price and the costs of delayed deliveries.*

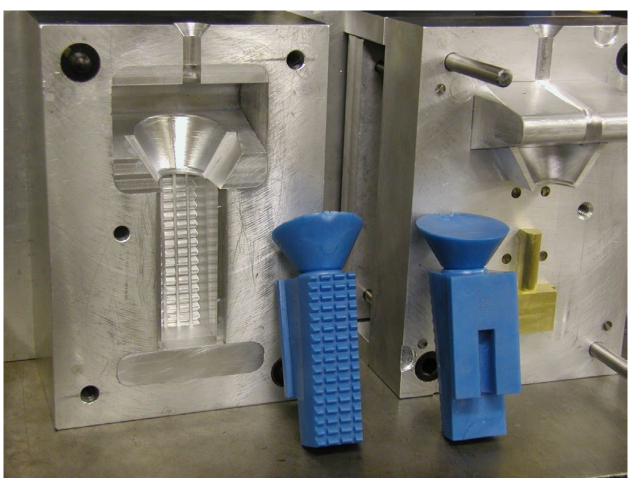

Figure 4. Investment casting die with resulting wax pattern. (Artwork courtesy of Texas Precision Metalcraft.)

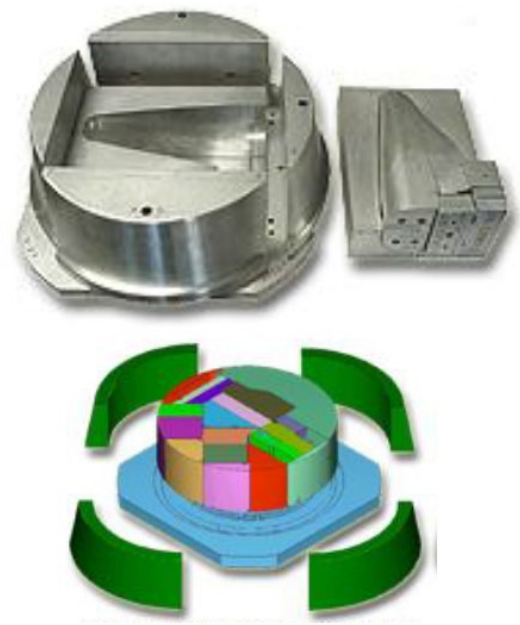

Figure 5. Compression Fixture for straightening. (Artwork courtesy of O'Fallon Casting.)

INVESTMENT CASTING MATERIALS

Fabrication alloys are often limited by what has always been used for an application, or what is on the shelf (Figure 6) of the fabrication shop (4340, A36 plate, etc.). However, metallurgy and heat treatment have advanced over time. There is a vast array of choices available for the designer when conceiving a part as an investment casting.

Fabricating alloys and investment casting processes/alloys have some overlap. The Investment Casting Handbook[2] has an entire chapter that can help you select the optimal choice. With this in mind, suppose the casting alloy under consideration is different, and possibly weaker than the fabrication/forging alloy. It is true that it might need to be made heavier in certain places. It is also true that the investment casting process will likely allow the component to be thinned out and made lighter overall. Examples[3, 4] are readily found of investment castings being more lightweight, even with new materials.

Also, certain materials have better castability than others in terms of thin wall conditions and heavy sections. It is often advantageous to ask about this early on before the final design is settled.

	Accuracy?	Relevance?
Investment Cast material is not necessarily the fabrication material	9.92	9.85
Investment Cast material flexibility = design options	9.85	9.92

Panel Comments on Materials:

- *An example of choosing an alternate material is that A201 aluminum is often specified for its high physical properties, but the castability is moderate to poor. On the other hand, F357 could give you similar (if lower) properties with better castability due to higher silicon. Perhaps the designer had not considered F357.*
- *We replaced a forging where the forging had superior mechanical properties. The casting had 30% lower strength, but the final part still weighed less.*
- *Sometimes it is not easy to change materials in certain industries.*
- *There should always be a discussion on alloy selection. Often one alloy potential alloy is cast often in your foundry and another is not; this means a great difference in minimum alloy purchase expenditures.*
- *80% of the time the cast alloy is different from the wrought alloy. The cast alloy is generally not as strong, so you have design modifications.*
- *An investment caster can and will help with this (material selection).*
- *A minor change in geometry can overcome a difference in material properties.*
- *A given foundry's familiarity with certain materials might be a limiting factor, but it is worth exploring early on.*
- *Material changes scare OEMs; there has to be a business case for re-approval. If you design for manufacture, you should consider multiple methods.*
- *Certain foundries have go-to materials that they produce frequently. This can affect your costs.*
- *A designer should always look at the cast alloy instead of reflexively picking the wrought alloy (like 7071 aluminum).*

Figure 6. Barstock at a machine shop. (Artwork courtesy of Seco Machine.)

LEAD TIME

Modern accounting and manufacturing trends demand shorter lead times than ever before. Also, the real world sometimes intrudes on our plans, and we end up with a need for a component right NOW. That said, the buyer needs to understand a few things about investment casting when this situation arises.

The investment casting process has an inherent time factor built into it. Even after development/launch, it is a time-consuming process to make a part. Creating wax patterns and subsequent shell room operations take days or weeks (the industry has been working on shortening this for a long time). The exact length can depend on part requirements.

If you need parts faster, you are probably looking for a solution with additive manufacturing at a substantial premium.

Also, subcontracted (subcon) processes (painting, machining, heat treatment, etc.) will add significantly to lead time, and the players involved might have limited control over these lead times. This is a real-world consideration, and engineering decisions have been made over this factor.

	Accuracy?	Relevance?
Investment Cast lead time can be days or weeks	9.92	9.92
Faster lead times might mean use of Additive Manufacturing	9.92	9.92
Subcon operations add time	9.92	9.92

Panel Comment on Lead Time:

- *At the time of this paper, pre-form core manufacturers have limited capacities, and their lead times can run up to 20 weeks for a simple core.*
- *One customer was in such a hurry we just made full production from SLA patterns.*
- *AM will not likely help on existing jobs with tools.*
- *Lead times can totally depend on your foundry of choice.*
- *Lead times are based on time to create the part and how quickly the PO is placed and how quickly the decision is made. Sometimes 25-30% of the lead time is the Purchasing decision-making process.*
- *SLA patterns allow for process development concurrently with tooling manufacture.*
- *With some Additive Manufacturing options (like printing an actual part), the materials do not have published accepted material properties.*
- *First articles can slow things down.*
- *Customers measure everyone on On-Time Delivery.*

GENERAL QUALITY REQUIREMENTS

Quality requirements need to ensure the desired output, not more. Acceptance criteria for form, fit, and function need to be:

- Reasonable
- Attainable
- Measurable

Reasonable in this context means avoiding dramatic absolute verbiage, such as “no weld repair,” unless it is genuinely needed. They are often grounded in non-technical ideas on quality. For example, some aerospace castings are weld repaired, and there is an SAE specification for this[5]. Such verbiage can result in multiple sources simply not returning a quote.

Not all foundries are qualified to supply all needs; a visit/audit might be needed. It has to be the right fit in terms of equipment, certifications, size capabilities, etc. A site visit is almost always a good idea, and eventually an audit.

Though it seems basic, a common occurrence as parts transition from fabrication to casting is contradictory specifications. A key to avoiding such problems is early clarity on the sequence (hierarchy) of compliance. For example, a common such sequence is:

1. PO
2. Print
3. Industry Specs
4. Local Specs

	Accuracy?	Relevance?
Quality requirements need to ensure the desired output, not more	9.92	9.92
Not all foundries can meet all needs	9.92	9.92
Be clear on sequence of compliance	9.92	9.92

Panel Comments on General Quality Requirements:

- *The print and model cannot conflict and have to cover everything.*
- *This (conflict in specs) does happen. A good foundry will have a review for contradictory specs.*
- *Think about function, function, function.*
- *The most important aspect is that you accurately describe what you are looking for, so your supplier understands what you require, so they can accurately forecast their ability to meet these needs. Often suppliers do not fully understand the requirement and you only find out later.*
- *Fit, form, function, not perfection.*
- *If they intend to use subcontractors like heat treating, those same requirements need to be flowed down to them also. This needs to be made clear on the PO.*
- *Sequence of compliance is important. For example, gating allowance does not supersede required print dimensions per ASTM.*
- *Be sure to understand system-level requirements beyond first articles.*
- *The designer should be judicious in not over-specifying NDT testing and tolerances beyond what is needed.*

QUALITY REQUIREMENTS, TEST BARS/COUPONS

Verification of material properties is done by test bars. As stated by White[6], “It is essential to have mechanical property test plans discussed before starting a new project. Separately cast then subsequently machined test bars are the best path forward for material assessment… (and) (buyers and suppliers) should discuss and agree on a mechanical properties testing plan, at the beginning of each new project.”

If you are going to utilize test bars for your components, there should be clarity regarding:

- Are they cast integrally (Figure 7) or separately cast?
- If cast integrally, does the location make sense?
- Handling during heat treat and other operations
- Number
- Coupons vs production volume

It is also important to recognize that the numerical value generated by the separate test bar does not necessarily reflect the properties of the entire casting, but rather the quality of the steel[6].

	Accuracy?	Relevance?
Test Bars verify quality of the metal.	9.77	9.92
A plan for test bars needs to be in place before production.	9.92	9.92

Panel Comments on Test Bars:
- *Cutting test bars from castings is expensive; you have to pay for the test, and the casting.*
- *When you are developing a new part, it might be useful to measure variations in material properties in different areas of the casting. You should know where you are most sensitive, and you should measure key characteristics there.*
- *The same applies for flat tensile bars.*
- *Identifying test bars is an important topic.*
- *Most commercial castings can be verified without the need for test bars using chemistry and heat treatment lab results. This is an avenue for cost savings and lead time reduction.*
- *Test bars test for microstructure, but there can be defects in the test bars. They can point to defects in the casting.*
- *Insure an adequate number of test bars in case of rework.*

Figure 7. A casting showing an integrally cast test coupon. (Artwork courtesy of Uni-Cast, LLC.)

CERTIFICATIONS

It is critical that the foundry and the buyer have a common understanding of what is expected in terms of certifications.

This should be clearly stated in the RFQ and PO. This topic is commonly covered in industry standard specifications, such as those used in aerospace applications. That said, depending on the industry, the designer/buyer might want to evaluate what is needed for the individual application.

Certifications can cover chemistry, hardness, tensile testing, microstructure, and other metrics. Some of this testing is done at the foundry and other testing might need outside lab work.

Some certifications and lab work might need to be broken out as a separate item on your invoice. Whether the tests are done on-site or at an outside lab, there are real costs involved. This is another case where over-specifying can just mean extra costs.

Lastly, you should never assume any certification or test is being done unless it is specifically stated as being done. For example, do you really need a remelt chemistry to be included after melting a master heat? This would need to be specified.

	Accuracy?	Relevance?
A cert plan should be agreed upon in advance	9.92	9.92
Certs have costs, internal and/or external	9.92	9.92

Panel Comments on Certs:
- *One heat treat lot might include four separate melt lots. They are certified separately.*
- *Traceability and date codes are important between melt lots and finished product. This includes heat treatment.*
- *If you have a certificate of conformance, that tells you it has met a standard. This is different than inspections.*
- *If parts are serialized, then the certification and all traceability need to be tied back correctly.*
- *Be very specific about the level of detail required in the certification report. For example, you might need an oven chart from a heat treater.*
- *You do not want untraceable certs when problems happen.*
- *Some foundries will do certain tests routinely and others test at the customer's request.*
- *Tests should be itemized out on the quote. New buyers tend to not understand this unless it is itemized.*

DIMENSIONS

The investment casting process is capable of achieving certain dimensional tolerances. These are not machine tolerances. Even so, you might not always need machine tolerances.

There are different ideas about what to expect. In general, the typical[1] tolerances supported by the investment casting process are:

- Linear: 1″ ± .010″; add .005″ for each add'l inch

Table 1 shows what is considered industry standard from the Investment Casting Handbook[2]. Your source might be different.

This should be discussed prior to determining final design and machining requirements. The source foundry should readily provide what they are comfortable with.

Table 1. Typical Linear Tolerance of Investment Castings

LINEAR TOLERANCE	
DIMENSIONS	*NORMAL*
up to 1"	± .010"
up to 2"	± .013"
up to 3"	± .016"
up to 4"	± .019"
up to 5"	± .022"
up to 6"	± .025"
up to 7"	± .028"
up to 8"	± .031"
up to 9"	± .034"
up to 10"	± .037"
> 10" allow ± .005" per inch	

An exception to the Linear Tolerance exists on wall thickness where the tolerance must be a minimum of ± .020"

Panel Comment on Dimensions:

- *Most foundries will publish their particular tolerancing limits on the web site. I have seen as low as .004" per inch per inch but normally .005" per inch per inch for linear and profile dimensions. Anything tighter would have to be agreed to with the foundry and customer, which is why new parts should always be discussed with the foundry at the design stage to ensure all features are practical and cost effective for the manufacturer and customer. Over specifying tolerances which cannot be achieved with the process are the cause of much of the price escalation and delivery delays seen in the industry. Tight tolerance features should have machine stock on them and be achieved by machining.*
- *Early input is critical. Insisting on overly tight tolerances or properties after final design can mean the ruin of the entire project. We have seen casting go back to barstock for no other reason, and it could have been avoided if the designer had accepted foundry input at the early stage.*
- *We will commonly have a fixture for checking the critical dimensions.*
- *Every part is its own animal. Their geometries are different.*
- *The dimensioning scheme on the drawing is very important, tying back to real casting features wherever possible and keeping the origin point as close to the center of mass to help keep dimensional tolerances.*
- *Your datum structure must match your GD&T protocol. Having a machined drawing helps, even if the foundry is not doing any machining.*
- *Your datum structure should be friendly to both CMM (Figure 8) and scanning technology.*

SURFACE FINISH

Surface finish is a common selling point for those in the investment casting industry as compared to other processes. According to the ICI[1], the investment casting process typically supports maintaining a surface roughness of 125 RMS max. White[7] explains, "Surface finish requirements are usually implied in discussions and loosely referenced as an RMS or Ra value. Little discussion occurs about the functional reason for the finish unless it is an airflow requirement in a turbine engine casting. There is usually no supplementary discussion or agreement between the casting purchaser and the casting manufacturer beyond this." The end user simply expects what they consider to be a superior surface finish compared to other processes.

To avoid future setbacks, surface finish should be specified on the print and/or RFQ. This includes indicating on the drawing the critical surfaces involved. The specification should be tied to a coupon or standard, such as the C-9 surface comparator (Figure 9). White[7] goes on to suggest that the designer "Utilize ANSI/ASME B46.1 to write the surface texture/finish drawing requirement/casting specification".

The designer/buyer should also understand that over- or under-specifying surface finish has a cost. That is, demanding a smoother finish than the part actually requires in service means devoting resources to meeting this requirement, and there are costs to those resources. These costs might not be obviously quantifiable; as such, it is wise to consult the foundry as to what is attainable at what cost.

With that in mind, the buyer should also know that the casting surface finish can vary depending on the source (between different investment foundries). If dual sourcing, this can lead to parts that are functionally identical but possess different appearances.

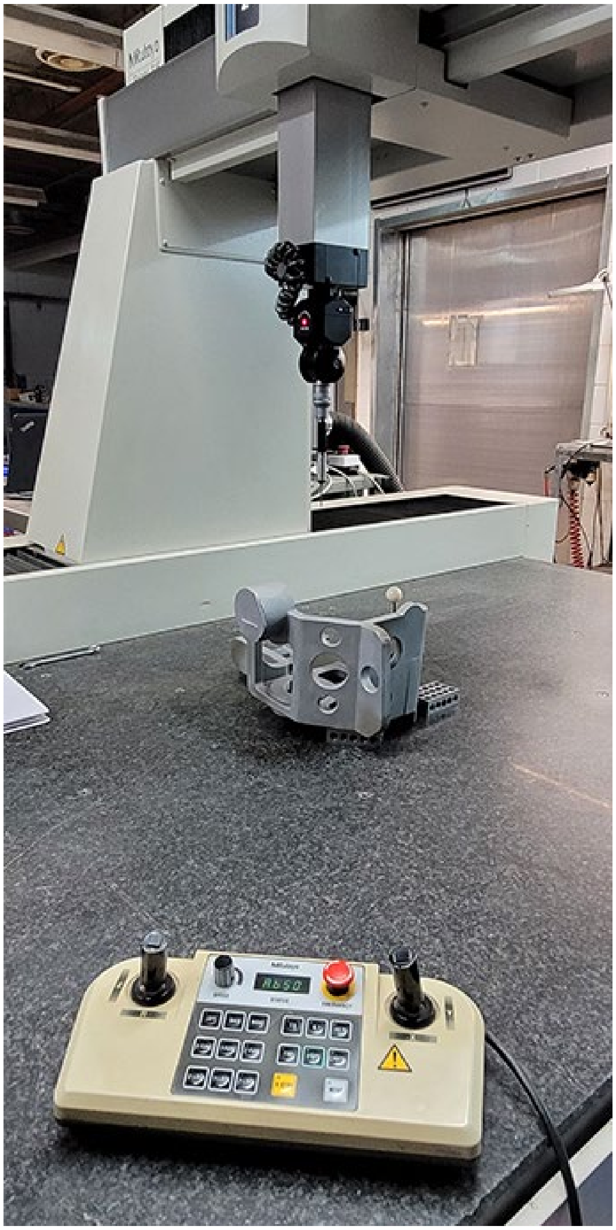

Figure 8. A casting undergoing dimensional inspection. (Artwork courtesy of Designed Precision Castings, Inc.)

	Accuracy?	Relevance?
Surface finish should be specified on the print and/or RFQ	9.92	9.92
Over- or under-specifying surface finish has a cost	9.92	9.92
Casting surface finish can vary depending on the source	9.92	9.92

Panel Comment on Surface Finish:

- *It makes little sense to demand or pay extra for surface finish you do not need. This adds to your cost and to your supplier's cost. It is easy to spend $1000 on a $20 part.*
- *We once had to buy a gage for our customer to measure surface finish on our parts.*
- *Gating locations can and do affect dimensions and surface finish. Ideally the gate will be on a surface that is later machined or does not affect fit, form, and function.*
- *There is a big difference between a tooled surface finish and a surface finish made from Additive Manufacturing.*
- *It is challenging to measure. A good supplier will mention this.*
- *There are multiple ways to get the surface you need besides the mold cavity, but there are costs.*
- *Surface finish standards and visual acceptance criteria are becoming extremely challenging in aerospace. Specific criteria need to be flowed down.*
- *Surface finish requirements, real or perceived, often preclude the use of additive manufacturing, especially on internal features.*
- *Bad casting quality will lead to bad surface finish even on machined parts (latent defects).*
- *We use the C-9 gage; many foundries use it.*

Figure 9. A C-9 cast microfinish comparator recommended for the evaluation of as-cast surfaces by the comparison method. (Artwork courtesy of Impro Aerotek USA, Inc.)

X-RAY TESTING (RADIOGRAPHY)

Those new to casting quality might be interested in assuring a porosity-free part. With this in mind, they might specify X-ray testing of cast or cast and machined components as part of their quality program. Figure 10 shows an x-ray of an investment casting.

Generally, a sample size is provided in the spec.
If there is a failure in that sample, then 100% of that lot (that specific view) is to be x-rayed.

Designation of the x-ray class is important in keeping the price reasonable. Having a high-class designation requires 100% x-ray, when in reality you might only need to sample for your application.

Appropriate designation of x-ray grade is critical to the piece price due to the cost of the film and/or labor. Careful consideration needs to be taken when applying NDT grades on machined castings as compared to raw castings. For example, "machined casting grade B raw casting grade C" is a problem waiting to happen. In other words, why would you read the x-ray of a cast part to the standard of a machined part?

If you allow digital technology instead of film, this can be a path to reduced costs.

	Accuracy?	Relevance?
Designate class wisely if you are going to specify x-ray inspection	9.92	9.92
Digital can allow reduced costs	9.92	9.92

Panel Comments on X-Ray:

- *Outside lab techs have difficulty reading casting results.*
- *You need to know what you need and apply it; there are standards to help you.*
- *The thickness of your part matters. The foundry might be able to readily x-ray a part three inches thick. They might outsource a thicker part.*
- *Specifying "high soundness" areas while maintaining flexibility elsewhere can be an avenue to savings.*
- *We typically do fluorescent penetrant inspection (FPI) on most castings as well. FPI will detect cracks, surface oxides, etc.*
- *X-ray cannot find everything. Also, you should specify it correctly to get what you want.*
- *The purpose of the x-ray should be detecting conditions that affect fit, form, and function.*
- *Digital and film x-rays are not the same; do some research before switching.*
- *The Grade you specify drives costs.*
- *Insure that any requirement for external approval for x-ray technique is specified in the PO/quote package. This could affect lead time.*
- *A machining drawing will typically include the acceptable grade for the machined part; it should match the cast part.*
- *A machining drawing will also tell you which areas do not matter (they might be getting removed).*
- *Machine shops will typically only do NDT on the machined areas.*
- *A partial sampling inspection plan (common with x-ray) might still lead to problems after machining. This is commonly called a latent defect.*

Figure 10. An x-ray of a production casting. (Artwork courtesy of O'Fallon Casting.)

FIRST ARTICLE SAMPLES

All parties want the initial samples to be produced quickly and at minimal cost. That said, they need to be meaningful. Your first article procedure should be reflective of your stable process with appropriate sample quantities representing regular variation. At the very least, a full set of mold cavities needs to be represented.

Also, different industries have different practices and customs. In investment casting, it is normal that these metal castings are paid for, even if the part is being sectioned for quality/inspection purposes.

At this stage, there is common precedent for a determination of parts being acceptable, with some detail out of spec that all parties agree is meaningless (maybe the overall width is 0.005" too great on paper, but functionally irrelevant). Parts go into production with a side goal of changing the drawing to reflect the new reality. However, people can get busy, and the drawing is never updated. Eight years later an engineer discovers 14,000 useful parts are out of specification. The point here is that when a drawing is supposed to be updated, even on something seemingly unimportant, then it should be updated expeditiously. Also, until the drawing is updated, a deviation should be provided.

This is also a common time for another specific mishap. If sample parts are being sent to a customer or subcon vendor, those samples should be shipped to a specific person at a specific address, with a tracking number. Many companies have multiple addresses, and samples have been known to get lost.

Lastly, surface finish of prototype parts made by rapid prototyping might not meet surface finish specifications. Chances are, there will be some dimensions that are non-compliant also. All parties should keep this in mind.

	Accuracy?	Relevance?
First article procedure should be reflective of your stable process	9.92	9.92
It is normal that sample metal castings are paid for	9.92	9.92
When a drawing is supposed to be updated, it should be updated	9.92	9.92
Ship samples to a specific person at a specific place	9.92	9.92

Panel Comments on First Article Samples

- *A good practice is to use a box that is brightly labeled such that it draws attention.*
- *Most buyers/designers think of first articles as "dimensional." In reality, it is also an approval of metallurgical soundness.*
- *"Not correcting the drawing" can be an extremely expensive experience for all involved, up to hundreds of thousands of dollars.*
- *Many SLA patterns will affect the surface of the shell.*
- *Updating drawings is required per ISO.*
- *You should clearly differentiate between prototypes and first articles.*
- *If you are going to use scanning technology for inspection, that needs to be agreed up front.*
- *This step tends to hold up the entire process.*
- *Samples get lost all the time. Did they go into production?*

HIDDEN COSTS

There can be some costs that are incurred in the investment casting process that are not readily apparent. Some of these are readily avoidable.

Relocating a part

- Sometimes in the course of a business relationship there comes a time to move a component from one source to another. There could be any number of reasons. When doing this, the buyer should consider:
- New tooling – is the existing tooling compatible with the new source's equipment? Sometimes it can be reworked or adapted, sometimes it cannot.
- Re-qualification – will your customer require engineering time and resources to re-qualify the part from the new source? The PPAP process, in particular, can be expensive.
- Production or service status – is the part going from full production to service status necessitating the move? If so, then many factors will change, and this will affect pricing.
- Engineering time – even without re-qualification, will you require internal resources to make the move happen?
- New pricing upon return – if the move fails, it is possible that the old pricing will not be honored upon return to the original source.
- Shipping – freight, brokerage, and time in transit are quantifiable costs that need to be considered.

Surcharges

The raw materials inputs used by foundries can vary in price considerably over time. These inputs include things like energy and alloy (nickel, molybdenum, etc.).
Some foundries (especially ferrous foundries) structure their pricing to have a base price and a surcharge based on these raw material price fluctuations. Some do not (Figure 11). When comparing the price of castings between two foundries it is imperative that these surcharges are calculated correctly[8]. If surcharges apply, then the conditions under which they will apply should be agreed upon up front.

Surcharges are generally a non-factor in nonferrous foundries using certified ingot.

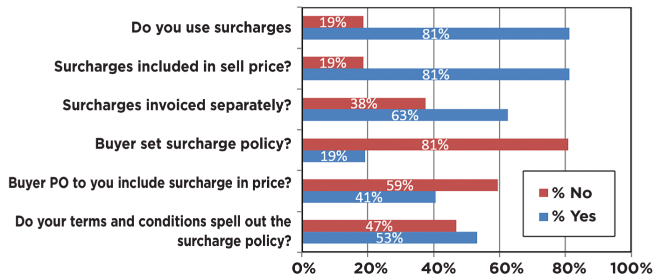

Figure 11. Survey results of general metalcasters on use of surcharges[8]. These results may or may not be indicative of the subset of investment casters; it is important to discuss this topic with your source.

Subcon markups

Suppose the buyer is buying a component from a foundry, and the foundry is providing that component cast, machined, heat treated, and painted condition. The casting and machining are done in house, and the heat treatment and painting are subcontracted.

That foundry will mark up the subcon operations (heat treat, painting, etc.) if the internal capability does not exist. When you purchase a heat treated and/or machined casting, the typical arrangement is to let the foundry handle the subcontracted vendor. They normally have a network of reliable suppliers set up.

The vendor will normally mark up the cost of these operations by some percentage. This is common and acceptable behavior; the foundry is managing the vendor, carrying the dollars, and taking responsibility for the quality of the part.

If the buyer wants to avoid these markups, the foundry will usually be glad to provide a raw casting to be processed by the buyer's own network of service providers.

Quantity requirements

At the time of this publication, the Investment Casting industry looks to be busy for the foreseeable future. Steady flow is important, as ramping up with additional labor is not realistic in contemporary labor markets. With these things in mind, a distinction needs to be made between whether the buyer needs 10,000 pieces all at once or 10 pieces per month for 30 years. A one-time 10,000-piece surge will require a premium because you would be overwhelming the source.

Just In Time

Also, Just-In-Time is an important concept. But in many foundries (and subcons), there are set-up fees. Paying short-run premiums at the foundry, heat treater, and machine shop can overwhelm the savings of making extra parts and carrying inventory.

PPAP

Lastly, the PPAP process is time-consuming, and many foundries (and subcons) charge a fee for these documents. This is sometimes, not always, broken out as a separate line item on the invoice/quote.

	Accuracy?	Relevance?
Relocating a part has hidden costs	9.92	9.92
Surcharges might or might not exist in your quotes	9.92	9.92
Companies routinely mark up the fees of subcons	9.92	9.92
You will likely pay a premium for surge work vs steady work	9.92	9.92
Small lot orders mean set up fees and premium pricing	9.92	9.92
PPAP fees can be charged and are sometimes a separate line item.	9.92	9.92

Panel Comments on Hidden Costs:

- *When relocating a part, you might see significant dimensional differences simply based on foundry wax and sand choice.*
- *Stocking raw or finished castings has its place.*
- *When tools travel from shop to shop, their condition might change.*
- *Some portions of some tools are considered intellectual property of the foundry. Removal of these portions means mutilating the tool.*
- *Just because something is not itemized does not mean it is free.*
- *You might be better off just ordering a new tool. We all have different waxes, different shells, etc.*
- *The standard of the industry is shipping +/- 10% on shipments unless agreed otherwise.*
- *Economical order quantities should be negotiated up front with the foundry.*
- *Modification charges are common when moving a tool. For example, shrink factors might be different.*

ADDITIVE MANUFACTURING AND INVESTMENT CASTING

Additive Manufacturing (AM) technology changes rapidly, with advancements being made on all fronts. There are many ways to use AM in investment castings:

- Printed resin or wax patterns
- Printed tooling
- Printed fixturing
- Printed cores
- Printed molds
- Etc.

In the context and timing of this paper, you can and should readily prototype with AM technology in any of the applications listed above. Figures 12 shows an example of a tool made by additive manufacturing[9], and Figure 13 shows a rendering of the wax pattern[9] made from that die.

Figure 12. An example of a part of a die for making a wax pattern produced by Additive Manufacturing.[9]

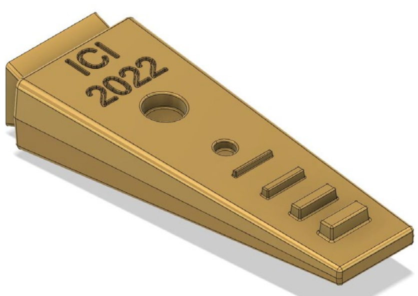

Figure 13. A rendering of the wax pattern produced from the AM die.[9]

Also, some designs make sense in AM for full production (as in printed waxes). If you are doing a short run of a part with any complexity in the tooling design, you should seriously consider AM.

Also, time is money. Tooling for wax patterns can be printed in a short time frame, as well as the patterns themselves. If you need parts in three weeks, you should probably just go straight to printed patterns.

That said, in other cases you are better off just building a tool. It is easy to think, "this is the future," and in some cases it is, but certain designs just make more sense economically with regular tooling.

The choice gets down to straight arithmetic regarding:
- How complex is the part?
- How many do you need?
- How soon do you need them?

	Accuracy?	Relevance?
AM technology changes rapidly in the world of Investment Casting	9.92	9.92
AM offers multiple options to the Investment Casting designer and buyer	9.92	9.92
Some parts can be Investment Cast in full production using AM technology	9.92	9.92
Some designs are better off as traditional tools, and paying a premium for AM technology is not a fit	9.92	9.92
The application of AM is a question of complexity, number of pieces, and time factors	9.92	9.92

Panel Comments on Additive Manufacturing:
- *You need to weigh AM case by case. It is not always obvious. As simple part conventional tooling might be cost competitive. On a complex part, AM may or may not deliver the surface finish or tolerances needed. On long running things that do not change, conventional tooling has a high up-front cost and much lower later costs.*
- *You need to know how your additive supplier prices the work. Is it by the dollar per cubic inch? Or machine time? Etc.?*
- *You cannot do AM without a CAD model.*
- *Having your own machines (i.e., SLA models) makes you more competitive.*

WHAT TO INCLUDE IN THE PURCHASE ORDER

The Purchase Order should reflect the same items covered in the Request for Quote, items such as:

- Part Number
- Drawing Number, including Revision Level
- Quantity Ordered
- Purchase Order Number
- Piece Price
- Date Required
- Buyer's Name
- Ship To Address and Bill To Address
- Material Certification Required
- Heat Treat Condition Required
- Any Other Certification or Testing Required

In addition, real-world experience has shown that packaging requirements can become critical at this point. Expensive parts can be damaged late in the manufacturing process.

For example, when parts are sent for heat treatment or machining, the subcon will often process the parts and re-package them in the same packaging in which they arrived. This may mean less than ideal protection for finished parts.

	Accuracy?	Relevance?
The PO should reflect info from the RFQ	9.92	9.92
Packaging is an often-overlooked aspect at this stage in sourcing	9.92	9.92

Panel Comments on the Purchase Order:
- *We commonly have special packaging for high volume jobs.*
- *Special packaging considerations should really be covered at the RFQ.*
- *The PO is the overriding document. It should include the quality requirements*
- *Including the wrong revision of the drawing in the PO is a common mistake.*

CONCLUSIONS

- A clear consensus exists across the Investment Casting industry, including the customer base on some critical topics in component purchasing and design.
- Investment castings can often offer an avenue to cost savings for OEMs as an alternative to fabrications and forgings.
- Customer support makes a huge difference in the successful conversion from fabrication/forging to casting.
- The investment casting process offers multiple creative methods to optimize component design and material.
- Tooling quotes need to be scrutinized correctly.
- Open and early communication between the buyer and the potential supplier is critical to maximize savings and minimize costly missteps.
- Cooperation can also help to reduce lead time.
- Clearly specifying realistic quality requirements for fit, form, and function is recommended. This includes test bars, surface finish, and x-ray testing.
- Dimensional capabilities vary between foundries and often from job to job, depending on geometry.
- Drawings should be updated when they need to be updated.
- There can be hidden costs in the investment casting process. They can often be avoided or minimized readily.
- Additive Manufacturing is a powerful tool in the investment casting toolbox. It should be considered and applied wisely.
- You might want to think about packaging for your finished parts.
- A condensed version of this paper is available in Appendix 1 for easy reference. Some edits have been made for brevity and space concerns. In case of any conflict, the original verbiage supersedes that in the Appendix.

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Appendix

The Investment Casting Conversion Process: An Industry Consensus

Condensed Version (some edits have been made for brevity; original version supersedes)

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INVESTMENT CASTINGS V. FORGINGS, WELDMENTS

There are applications where using an investment casting will reduce overall cost, weight, no. of SKUs (part numbers), and reduced assembly costs. There are also applications where an investment casting is not a fit. The foundry will tell you so. The most important factor is getting an experienced designer to consider a casting as a design option as early in the process as possible.

The most common barrier to the weldment-to-casting conversion process is tooling cost. That said, tooling cost is not what it used to be. Lastly, as a buyer/designer, you likely have multiple domestic casting producers available.

KEY TAKEAWAYS:

- You can often cut significant costs going from fabrication/forging to casting.
- Tooling cost, a traditional barrier, is not what it used to be.
- There are multiple domestic Investment Casting foundries.

PANEL COMMENTS ON INVESTMENT CASTINGS VS FORGING, WELDMENTS:

- Beyond tooling costs, qualification costs need to be considered for existing designs (so earlier is better).
- Site visits at the foundry can inspire the beginning designer by showing other casting designs.
- Once the wax die is certified, you can count on the reliability of those dimensions for decades as compared to machining and forging.
- It is very part-specific, regarding how much money you can save.
- Your choices as a buyer will vary depending on alloy and size envelope especially.

- In my experience, the greatest barrier in going from a weldment to a casting is getting customer engineering design and support.
- In aerospace, you do not traditionally convert forgings to castings. You are more likely to convert a part that was hogged out of barstock.
- There are more tooling options available today. Printed tooling for cores, printed cores, etc.

WHAT TO INCLUDE IN AN RFQ FOR AN INV. CASTING

If a decision has been made to produce a part as an investment casting, then at some point a Request for Quote (RFQ) will likely be generated to go to potential sources. The buyer will want meaningful quotes. Below are guidelines for what to include in an RFQ for an investment casting:

DRAWINGS, INCLUDING PART NUMBER, PART NAME, AND REVISION LEVEL.

- Casting drawing in .pdf format,
- If machining is required, there should be a machined casting drawing.
- It would be beneficial to indicate critical areas on the casting, including preferred or designated machining locating areas.
- Ideally, model files in the appropriate format will be provided.

MATERIAL TYPE

- RFQ should list the type & grade of material required (should be on drawing, too).

PROTOTYPE OR PRODUCTION?

- This is important information, as it lets the foundry know whether to quote prototype or production tooling as well as whether assistance with rapid prototyping is required.

VOLUMES

- Estimated annual usage (EAU), incl. lot sizes and frequencies
- If prototypes are required, the volume of prototype pieces

PART WEIGHT

- Accurate part weight (often misstated, will impact pricing).

VALUE-ADDED OPERATIONS

- Any paint/powder/etc., Machining, Heat Treatment

CERTIFICATIONS

- Any material certs or special testing, NDT requirements, including X-ray
- Which standards are required as part of the certification?

Timing

- Time requirement to return the quote (outside tooling will add time)
- Sample start date and production start date.

Panel Comments on What to Include in an RFQ:

- At the prototype stage of the process, it is very important to glean manufacturability input from the foundry for your design. The prototype cost might not reflect the final cost, in either direction.
- 3D CAD models are critical. This is the 21st century. You need models to understand the castability of the part and the complexity of the tooling that will be needed.
- Foundries do a lot of quotes, and land comparatively few jobs. Does it even make sense to send this RFQ to this shop? Are they a fit? Or am I wasting everyone's time?
- Models are almost mandatory. If a part is being re-sourced and there is no model, we will commonly 3D scan the existing part .
- It is a good practice for the vendor to reply to your RFQ the same day to at least acknowledge that you received the RFQ.
- There needs to be a fit between the customer and the foundry in terms of equipment and other factors.
- Be as straightforward as possible on EAU.
- Quotes take time, often several hours. “Fishing” quotes are easy to detect and are not taken seriously.
- After we get the RFQ, we will commonly have a conference call with recommendations and exceptions before submitting quote.
- Casting drawings should specify surface condition requirements by surface; they should indicate allowances for gates, etc.
- If the part has export controls, this needs to be noted.
- Often the casting design may call for a simple and inexpensive part but overdoing the notes and restrictions can drive up the overall cost significantly.
- In general, the issue with RFQs is that they are not specific enough. They are stated in a way that backs the supplier into a corner, and the supplier will no-quote.
- APQP and PPAP requirements should be presented up front.

INVESTMENT CASTING TOOLING

With a few exceptions, investment casting tooling belongs to the customer. Investment casting tooling includes more than the die that produces the wax pattern. There are other types of tooling, such as straightening fixtures, machining fixtures, core tooling, etc. These items can vary, and some can rise in complexity and cost to rival the main die.

When getting a quote on tooling, your tooling costs, either up front or amortized, will vary from foundry to foundry depending on program requirements, quantities, lot sizes, etc. For example, one foundry might quote a straightening fixture immediately, thinking it a necessity. Another might exclude such an item, thinking it unneeded. When comparing quotes, these line items should be noted.

Also, if a buyer sees a massive difference (multiples) in tooling prices between two sources, then this is worth an inquiry. It is possible something has been overlooked or misunderstood. Lastly, rework, maintenance, and gating of tooling can be costly. This should be discussed openly.

KEY TAKEAWAYS:

- Investment Casting tooling can include many pieces
- Multiple factors drive tooling cost
- Large differences in tooling quotes warrant a close look

PANEL COMMENTS ON TOOLING:

- Not all tooling quotes are the same; one shop might include CMM fixture, etc.
- There is a lot of benefit to having a bona-fide tool room in the foundry; there is a synergy to the collaboration between the tool room, the wax room, the shell room, and the melt shop.
- Unusually cheap tooling quotes warrant exploration. Why so cheap? Did they omit something? Chances are that when production starts there will be another tool required and another bill.
- Compression straightening can be 60% of the cost of a tooling pkg.
- All tooling belonging to the foundry should be hard-tagged and photographed indicating ownership for asset tracking purposes.
- The need for a straightening fixture can be 60% of the tooling cost. If the piece cost is low, this is justified to reduce labor.
- You can minimize straightening issues and tooling costs with casting design and casting process optimization using numerical simulation tools.
- The wax die can be tool steel or aluminum, for example. We could go on all day on the differences in tools.
- The use of external solubles instead of complex finished die tooling can make a huge difference in cycle time & finished cost.
- Tooling cost is heavily influenced by product volume. You might need a more expensive die for higher volume. More automated tools cost more. Piece price and tool price go together.
- Before building a tool, do a process simulation to optimize the gating, etc.
- Foundry quotes tend to neglect including gages even when the drawing indicates that a feature is to be gaged.
- Canadian/US exchange rate impacts tooling/casting quotes a great deal. At the time of this writing, the difference is 30%.
- A multi-cavity die might be more expensive but would be suited to high volume parts. This might be worth it to offset higher piece price and the costs of delayed deliveries.

INVESTMENT CASTING MATERIALS

Fabrication alloys are often limited by what has always been used for an application, or what is on the shelf of the fabrication shop.

However, there is a vast array of choices available for the designer when conceiving a part as an investment casting.

Fabricating alloys and investment casting processes/alloys have some overlap. The Investment Casting Handbook has an entire chapter that can help you select the optimal choice. With this in mind, suppose the casting alloy under consideration is different, and possibly weaker than the fabrication/forging alloy. It is true that it might need to be made heavier in certain places. It is also true that the investment casting process will likely allow the component to be thinned out and made lighter overall.

Also, certain materials have better castability than others in terms of thin wall conditions and heavy sections. It is often advantageous to ask about this early on before the final design is settled.

KEY TAKEAWAYS:

- Investment Cast material is not necessarily the fabrication material
- Investment Cast material flexibility = design options

PANEL COMMENTS ON MATERIALS:

- An example of choosing an alternate material is that A201 aluminum is often specified for its high physical properties, but the castability is moderate to poor. On the other hand, F357 could give you similar (if lower) properties with better castability due to higher silicon. Perhaps the designer had not considered F357.
- We replaced a forging where the forging had superior mechanical properties. The casting had 30% lower strength, but the final part still weighed less.
- Sometimes it is not easy to change materials in certain industries.
- There should always be a discussion on alloy selection. Often one alloy potential alloy is cast often in your foundry and another is not; this means a great difference in minimum alloy purchase expenditures.
- 80% of the time the cast alloy is different from the wrought alloy. The cast alloy is generally not as strong, so you have design modifications.
- The investment caster can and will help with (material selection).
- A minor change in geometry can overcome a difference in material properties.
- A given foundry’s familiarity with certain materials might be a limiting factor, but it is worth exploring early on.

- Material changes scare OEMs; there has to be a business case for re-approval. If you design for manufacture, you should consider multiple methods.
- Certain foundries have go-to materials that they produce frequently. This can affect your costs.
- A designer should always look at the cast alloy instead of reflexively picking the wrought alloy (like 7071 aluminum).

LEAD TIME

Modern accounting and manufacturing trends demand shorter lead times than ever before. Also, the real world sometimes intrudes on our plans, and we end up with a need for a component right NOW. That said, the buyer needs to understand a few things about investment casting when this situation arises.

The investment casting process has an inherent time factor built into it. Even after development/launch, it is a time-consuming process to make a part. Creating wax patterns and subsequent shell room operations take days or weeks (the industry has been working on shortening this for a long time). The exact length can depend on part requirements.

If you need parts faster, you are probably looking for a solution with additive manufacturing at a substantial premium.

Also, subcontracted (subcon) processes (painting, machining, heat treatment, etc.) will add significantly to lead time, and the players involved might have limited control over these lead times.

KEY TAKEAWAYS:

- Investment Cast lead time can be days or weeks
- Faster lead times might mean use of Additive Manufacturing
- Subcon operations add time

PANEL COMMENT ON LEAD TIME:

- At the time of this paper, pre-form core manufacturers have limited capacities; their lead times can run up to 20 weeks for a simple core.
- One customer was in such a hurry we just made full production from SLA patterns.
- AM will not likely help on existing jobs with tools.
- Lead times can totally depend on your foundry of choice.
- Lead times are based on time to create the part and how quickly the PO is placed and how quickly is the decision made. Sometimes 25-30% of the lead time is the Purchasing decision-making process.
- SLA patterns allow for process development concurrently with tooling manufacture.
- With some Additive Manufacturing options (like printing an actual part), the materials do not have published accepted material properties.
- First articles can slow things down.
- Customers measure everyone on On-Time Delivery.

GENERAL QUALITY REQUIREMENTS

Quality requirements need to ensure the desired output, not more. Acceptance criteria for form, fit, and function need to be reasonable, attainable, and measurable.

Reasonable in this context means avoiding dramatic absolute verbiage, such as “no weld repair,” unless it is genuinely needed. They are often grounded in non-technical ideas on quality. For example, some aerospace castings are weld repaired, and there is an SAE specification for this. Such verbiage can result in multiple sources simply not returning a quote.

Not all foundries are qualified to supply all needs; a visit/audit might be needed. A site visit is almost always a good idea, and eventually an audit.

Though it seems basic, a common occurrence as parts transition from fabrication to casting is contradictory specifications. A key to avoiding such problems is early clarity on the sequence (hierarchy) of compliance. For example, a common sequence is:

5. PO
6. Print
7. Industry Specs
8. Local Specs

KEY TAKEAWAYS:

- Quality requirements need to ensure desired output, not more
- Not all foundries can meet all needs

PANEL COMMENTS ON GENERAL QUALITY REQUIREMENTS:

- The print & model cannot conflict and have to cover everything.
- This (conflict in specs) does happen. A good foundry will have a review for contradictory specs.
- Think about function, function, function.
- The most important aspect is that you accurately describe what you are looking for, so your supplier understands what you require, so they can accurately forecast their ability to meet these needs. Often suppliers do not fully understand the requirement and you only find out later.
- Fit, form, function, not perfection.
- If they intend to use subcontractors like heat treating, those same requirements need to be flowed down to them also. This needs to be made clear on the PO.
- Sequence of compliance is important. For example, gating allowance does not supersede required print dimensions per ASTM.
- Be sure to understand system-level requirements beyond first articles.

- The designer should be judicious in not over-specifying NDT testing and tolerances beyond what is needed.

QUALITY REQUIREMENTS, TEST BARS/COUPONS

Verification of material properties is done by test bars. Buyers and suppliers should discuss and agree on a plan for such testing early in the development process.

If you are going to utilize test bars, there should be clarity regarding number of bars, how they are cast (integrally or separately), etc.

It is also important to recognize that the numerical value generated by the separately cast test bar does not necessarily reflect the properties of the entire casting, but rather the quality of the steel.

KEY TAKEAWAYS:

- Test Bars verify quality of the metal.
- A plan for test bars needs to be in place before production.

PANEL COMMENTS ON TEST BARS:

- Cutting test bars from castings is expensive; you have to pay for the test, and the casting.
- When you are developing a new part, it might be useful to measure variations in material properties in different areas of the casting. You should know where you are most sensitive, and you should measure key characteristics there.
- The same applies for flat tensile bars.
- Identifying test bars is an important topic.
- Most commercial castings can be verified without the need for test bars using chemistry and heat treatment lab results. This is an avenue for cost savings and lead time reduction.
- Test bars test for microstructure, but there can be defects in the test bars. They can point to defects in the casting.
- Insure an adequate number of test bars in case of rework.

CERTIFICATIONS

It is critical that the foundry and the buyer have a common understanding of what is expected in terms of certifications.

This should be clearly stated in the RFQ and PO. This topic is commonly covered in industry standard specifications, such as those used in aerospace applications. That said, depending on the industry, the designer/buyer might want to evaluate what is needed for the individual application.

Certifications can cover chemistry, hardness, tensile testing, microstructure, and other metrics. Some of this testing is done at the foundry and other testing might need outside lab work.

Some certifications and lab work might need to be broken out as a separate item on your invoice. Whether the tests are done on-site or at an outside lab, there are real costs involved. This is another case where over-specifying can just mean extra costs.

Lastly, you should never assume any certification or test is being done unless it is specifically stated as being done.

KEY TAKEAWAYS:

- A cert plan should be agreed upon in advance
- Certs have costs, internal and/or external

PANEL COMMENTS ON CERTS:

- One heat treat lot might include four separate melt lots. They are certified separately.
- Traceability and date codes are important between melt lots and finished product. This includes heat treatment.
- If you have a certificate of conformance, that tells you it has met a standard. This is different than inspections.
- If parts are serialized, then the certification and all traceability need to tie back correctly.
- Be very specific about the level of detail required in the certification report. For example, you might need an oven chart from a heat treater.
- You do not want untraceable certs when problems happen.
- Some foundries do certain tests routinely; others test at the customer's request.
- Tests should be itemized out on the quote. New buyers tend to not understand this unless it is itemized.

DIMENSIONS

The investment casting process is capable of achieving certain dimensional tolerances. These are not machine tolerances. In general, the typical tolerances supported by the investment casting process are:

Linear: 1″ ± .010″; add .005″ for each add'l inch

This should be discussed prior to determining final design and machining requirements.

PANEL COMMENT ON DIMENSIONS:

- Most foundries will publish their particular tolerancing limits on the website. I have seen as low as .004" per inch per inch but normally .005" per inch per inch for linear & profile dimensions. Anything tighter would have to be agreed on with the foundry and customer, which is why new parts should always be discussed with the foundry at the design stage to ensure all features are practical and

cost effective for the manufacturer & customer. Over specifying tolerances which cannot be achieved with the process are the cause of much of the price escalation & delivery delays seen in the industry. Tight tolerance features should have machine stock on them and be achieved by machining.
- Early input is critical. Insisting on overly tight tolerances or properties after final design can mean the ruin of the entire project. We have seen casting go back to barstock for no other reason, and it could have been avoided if the designer had accepted foundry input at the early stage.
- We commonly have a fixture for checking critical dimensions.
- Every part is its own animal. Their geometries are different.
- The dimensioning scheme on the drawing is very important, tying back to real casting features wherever possible and keeping the origin point as close to the center of mass to help keep dimensional tolerances.
- Your datum structure must match your GD&T protocol. Having a machined drawing helps, even if the foundry is not doing any machining.
- Your datum structure should be friendly to both CMM and scanning technology.

SURFACE FINISH

Surface finish is a common selling point for those in the investment casting industry as compared to other processes. According to the ICI1, the investment casting process typically supports maintaining a surface roughness of 125 RMS max.

To avoid future setbacks, surface finish should be specified on the print and/or RFQ. This includes indicating on the drawing the critical surfaces involved. The specification should be tied to a coupon or standard. The designer/buyer should also understand that over- or under-specifying surface finish has a cost.

The buyer should also know that the casting surface finish can vary depending on the source (between different investment foundries).

KEY TAKEAWAYS:
- Surface finish should be specified on the print and/or RFQ
- Over- or under-specifying surface finish has a cost
- Casting surface finish can vary depending on the source

PANEL COMMENT ON SURFACE FINISH:
- It makes little sense to demand or pay extra for surface finish you do not need. This adds to your cost and to your supplier's cost. It is easy to spend $1,000 on a $20 part.
- We once had to buy a gage for our customer to measure surface finish on our parts.
- Gating locations can and do affect dimensions and surface finish. Ideally the gate will be on a surface that is later machined or does not affect fit, form, and function.
- There is a big difference between a tooled surface finish and a surface finish made from Additive Manufacturing.
- It is challenging to measure. A good supplier will mention this.
- There are multiple ways to get the surface you need besides the mold cavity, but there are costs.
- Surface finish standards and visual acceptance criteria are becoming extremely challenging in aerospace. Specific criteria need to be flowed down.
- Surface finish requirements, real or perceived, often preclude the use of AM, especially on internal features.
- Bad casting quality will lead to bad surface finish even on machined parts (latent defects).
- We use the C-9 gage; many foundries use it.

X-RAY TESTING (RADIOGRAPHY)

Those new to casting quality might be interested in assuring a porosity-free part. With this in mind, they might specify X-ray testing as part of their quality program.

Generally, a sample size is provided in the spec. If there is a failure in that sample, then 100% of that lot (that specific view) is to be x-rayed.

Designation of the x-ray class is important in keeping the price reasonable. Having a high-class designation requires 100% x-ray, when in reality you might only need to sample for your application.
"Machined casting grade B raw casting grade C" is a problem waiting to happen.

Allowing digital technology instead of film can mean reduced costs.

KEY TAKEAWAYS:
- Designate class wisely with x-ray inspection
- Digital can allow reduced costs

PANEL COMMENTS ON X-RAY:
- Outside lab techs have difficulty reading casting results.
- You need to know what you need and apply it; there are standards to help you.
- The thickness of your part matters. The foundry might be able to readily x-ray a part three inches thick. They might outsource a thicker part.
- Specifying "high soundness" areas while maintaining flexibility elsewhere can be an avenue to savings.

- We typically do fluorescent penetrant inspection (FPI) on most castings as well. FPI will detect cracks, surface oxides, etc.
- X-ray cannot find everything. Also, you should specify it correctly to get what you want.
- The purpose of the x-ray should be detecting conditions that affect fit, form, and function.
- Digital and film x-rays are not the same; do some research before switching.
- The Grade you specify drives costs.
- Insure that any requirement for external approval for x-ray technique is specified in the PO/quote package. This could affect lead time.
- A machining drawing will typically include the acceptable grade for the machined part; it should match the cast part.
- A machining drawing will also tell you which areas do not matter (they might be getting removed).
- Machine shops will typically only do NDT on the mach. areas.
- A partial sampling inspection plan (common with x-ray) might still lead to problems after machining. This is commonly called a latent defect.

FIRST ARTICLE SAMPLES

Your first article procedure should be reflective of your stable process with appropriate sample quantities representing regular variation. At the very least, a full set of mold cavities needs to be represented.

It is normal that sample metal castings are paid for, even if the part is being sectioned for quality/inspection purposes.

When a drawing is supposed to be updated, then it should be updated expeditiously. Also, until the drawing is updated, a deviation should be provided.

If sample parts are being sent to a customer or subcon vendor, those samples should be shipped to a specific person at a specific address, with a tracking number.

KEY TAKEAWAYS:

- First article procedure should be reflective of your stable process
- It is normal that sample metal castings are paid for
- When a drawing is supposed to be updated, it should be updated

PANEL COMMENTS ON FIRST ARTICLE SAMPLES

- A good practice is to use a box that is brightly labeled to draw attention.
- Most buyers/designers think of first articles as "dimensional." In reality, it is also an approval of metallurgical soundness.
- "Not correcting the drawing" can be a very expensive experience for all involved, up to hundreds of thousands of dollars.
- Many SLA patterns will affect the surface of the shell.
- Updating drawings is required per ISO.
- You should clearly differentiate between prototypes and first articles.
- If you are going to use scanning technology for inspection, that needs to be agreed up front.
- This step tends to hold up the entire process.
- Samples get lost all the time. Did they go into production?

HIDDEN COSTS

There can be some costs that are incurred in the investment casting process that are not readily apparent. Some are readily avoidable.

Relocating a part: Sometimes there comes a time to move a component from one source to another. When doing this, the buyer should consider:

- New tooling – is the existing tooling compatible with the new source's equipment? Sometimes it can be reworked or adapted, sometimes it cannot.
- Re-qualification – will your customer require engineering time and resources to re-qualify the part from the new source?
- Production or service status – is the part going from full production to service status necessitating the move?
- Engineering time – even without re-qualification, will you require internal resources to make the move happen?
- New pricing upon return – if the move fails, it is possible that old pricing will not be honored upon return to original source.
- Shipping – freight, brokerage, and time in transit are quantifiable costs

Surcharges: The inputs used by foundries can vary in price considerably over time. These inputs include things like energy and alloy (nickel, etc.). Some foundries (especially ferrous foundries) structure their pricing to have a base price and a surcharge based on these raw material price fluctuations. When comparing the price of castings between two foundries it is imperative that these surcharges are calculated correctly. Surcharges are generally a non-factor in nonferrous foundries.

Subcon markups: Suppose the buyer is buying a component from a foundry, and the foundry is providing that component cast, machined, heat treated, and painted condition. That foundry will mark up the subcontracted operations (heat treat, painting, etc.). This is common and acceptable behavior. If the buyer wants to avoid these markups, the foundry will usually be glad to provide a raw casting.

Quantity requirements: At the time of this publication, the Investment Casting industry looks to be busy for the foreseeable future. Steady flow is important, as ramping up with additional labor is costly. A one-time surge will require a premium.

Just In Time: n many foundries (and subcons), there are set-up fees. Paying short-run premiums at the foundry, heat treater, and machine shop can overwhelm the savings of making extra parts and carrying inventory.

PPAP: Lastly, the PPAP process is time-consuming, and many foundries (and subcons) charge a fee for these documents. This is sometimes, not always, broken out as a separate line item on the invoice/quote.

KEY TAKEAWAYS:

- Relocating a part has hidden costs
- Surcharges might or might not exist in your quotes
- Companies routinely mark up the fees of subcons
- You will likely pay a premium for surge work vs steady work
- Small lot orders mean set up fees and premium pricing
- PPAP fees can be charged and are sometimes a separate line item.

PANEL COMMENTS ON HIDDEN COSTS:

- When relocating a part, you might see significant dimensional differences simply based on foundry wax and sand choice.
- Stocking raw or finished castings has its place.
- When tools travel from shop to shop, their condition might change.
- Just because something is not itemized does not mean it is free.
- Some portions of some tools are considered intellectual property of the foundry. Removal of these portions means mutilating the tool.
- You might be better off just ordering a new tool. We all have different waxes, different shells, etc.
- Industry standard shipping +/- 10% on shipments unless agreed otherwise.
- Economical order quantities should be negotiated up front
- Modification charges are common when moving a tool. For example, shrink factors might be different.

ADDITIVE MANUFACTURING AND INVESTMENT CASTING

Additive Manufacturing (AM) technology changes rapidly. There are many ways to use AM in investment castings, such as printed resin or wax patterns, printed tooling, printed cores, etc.

You can and should readily prototype with AM technology in any of the applications listed above. Also, some designs make sense in AM for full production (as in printed waxes). That said, in other cases you are better off just building a tool. The choice gets down to arithmetic regarding:

- How complex is the part?
- How many do you need?
- How soon do you need them?

KEY TAKEAWAYS:

- AM technology changes rapidly in the world of Investment Casting
- AM offers multiple options to the Investment Casting designer and buyer
- Some parts can be Investment Cast in full production using AM technology
- Some designs are better off as traditional tools, and paying a premium for AM technology is not a fit
- Application of AM is a question of complexity, no. of pieces, & time factors

PANEL COMMENTS ON ADDITIVE MANUFACTURING:

- You need to weigh AM case by case. It is not always obvious. As simple part conventional tooling might be cost competitive. On a complex part, AM may or may not deliver the surface finish or tolerances needed. On long running things that do not change, conventional tooling has a high up-front cost and much lower later costs.
- You need to know how your additive supplier prices the work. Is it by the dollar per cubic inch? Or machine time? Etc.?
- You cannot do AM without a CAD model.
- Having your own machines (like for SLA models) makes you more competitive.

WHAT TO INCLUDE IN THE PURCHASE ORDER

The Purchase Order should reflect the same items covered in the Request for Quote. In addition, real-world experience has shown that packaging requirements can become critical at this point.

KEY TAKEAWAYS:

- The PO should reflect info from the RFQ
- Packaging is an often-overlooked aspect at this stage in sourcing

PANEL COMMENTS ON
THE PURCHASE ORDER:

- We commonly have special packaging for high volume jobs.
- Special packaging considerations should be covered at the RFQ.
- The PO is the overriding document. It should include the quality requirements

- Including the wrong revision of the drawing in the PO is a common mistake.

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