GRAINGER AND WORRALL

The Basics of the Sand Casting Process

A quick primer on how the sand casting process can create the complex geometric shapes needed to power 21st century technology.

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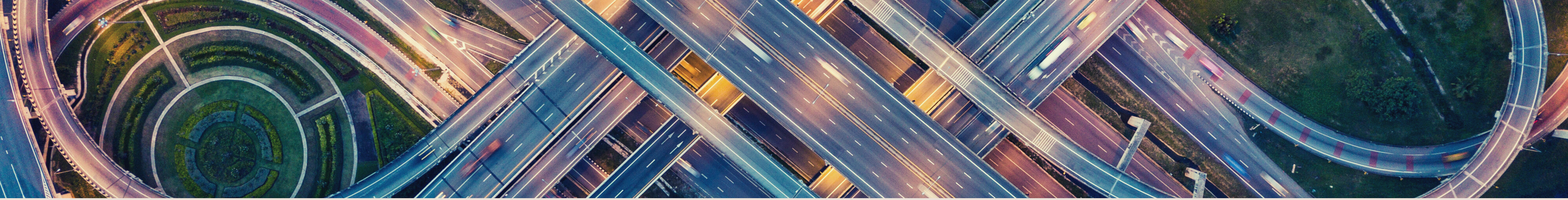
A QUICK OVERVIEW



Why we wrote this guide

IT'S ALL ABOUT EMPOWERING YOU TO MAKE INFORMED DESIGN CHOICES

Casting is a complicated process, with many different components that need consideration for successful part optimisation. We've written this guide on sand casting basics to help you fully understand the process; as well as how design function, material selection and the purpose of your part will impact the quality of the final casting.

We've also highlighted some useful questions that we're commonly asked, and questions that *you* can ask your supplier too for additional insights. These will help you achieve the optimal final function of your part, as quickly and as cost efficiently as possible; whether that's for Series production, or for prototyping a part.

At Grainger and Worrall, we're in the business of enabling **future shape technology.** Environmental concerns driving lightweighting and part count reduction demand castings with thinner walls, higher strength, and more complex geometric shapes. Our Purpose is to help the world achieve carbon-neutral aims with innovative castings.

Why choose sand casting?

A BRIEF INTRODUCTION

Sand casting is often misunderstood as a low tech production process. But this isn't true. While sand casting *is* one of the oldest production processes, modern sand casting uses technology to optimise the entire process; from initial enquiry stage through to production and inspection. Data-driven science has evolved sand casting massively in just the last 20 years, delivering a process that can achieve the complex castings needed to meet global 21st century challenges.

Sand casting has many advantages, especially in prototyping. It's a reliable, relatively quick, cost effective casting process; enabling highly complex parts to be created in almost any size, weight, or alloy and at low cost compared to other methods. As a process, it's almost 100% circular in terms of sustainability. However, sand casting doesn't suit all applications. For example, volumes greater than 10,000 are not suitable for sand casting. Your project requirements will determine the best process.

However, the flexibility and potential of sand casting allows for changes and optimisation in almost any part of the process. These include materials (alloys and sand used), the casting process methods chosen, finishing and validation methods. All of these can optimise the function and material properties required for your part.

Different ways to make a part

It's often incorrectly assumed that each casting process can achieve similar final castings in terms of quality, finish, function and complexity. Understanding the potential, as well as the limitations of each casting process is a vital first step in choosing the best manufacturing method for your part.

SAND CASTING

Sand casting involves pouring molten metal into a sand mould cavity, where it then cools and solidifies. After the metal has cooled, the mould is broken apart to remove the casting. Sand casting can produce complex net parts relatively quickly and cost efficiently compared to other processes. It's also a nearly 100% circular process with all the raw materials (sand and metal) being able to be reused.

INVESTMENT CASTING

A pattern is created from wax, which is then dipped into ceramic slurry. This is then heated and dried, creating a ceramic shell mould for casting. The wax flows out and the molten metal is poured into the cavity. Complex shapes can be created, particularly in industries such as aerospace and automotive. Smaller features can also be made compared to sand casting, for example air cooling ducts inside a Tungsten turbine blade. Mostly used for low production volumes.

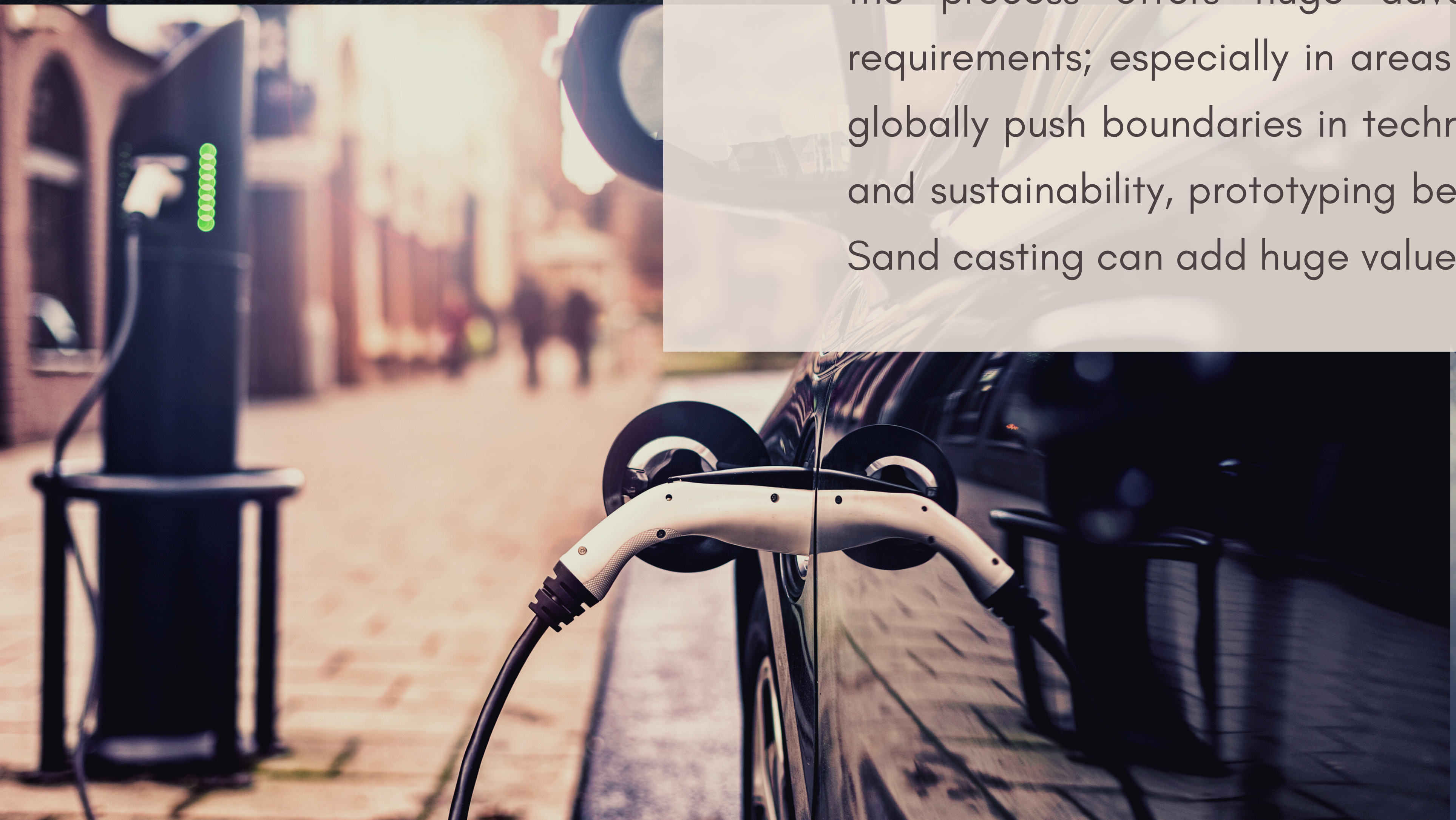
LOW/HIGH PRESSURE DIE CASTING

Both are repetitive methods. Low pressure die casting introduces metal into the chill mould from below where gas pressure holds the metal in the die until it solidifies. High pressure injects molten metal into a metal die under high pressure and high speed, allowing quicker casting production. High pressure part cost is lower than in low pressure casting, due to higher production volume capability offsetting initial investment costs.

OTHER METHODS...

Machining from solid - Parts are machined from billets of metal into the required shape using CNC machines.

3D Printing - An additive process where parts are made layer-by-layer. There are 7 main types of 3D printing, including laser sintering (SLS) and fused deposition (FDM). A wide variety of materials can be used to help create complex shapes, but it's slower and more costly for all but one-offs.



PROTOTYPING FOR FUTURE SHAPED TECHNOLOGY

While sand casting is one of the oldest manufacturing methods, the process offers huge advantages for future production requirements; especially in areas such as electric vehicles. As we globally push boundaries in technology, performance expectation and sustainability, prototyping becomes more and more essential. Sand casting can add huge value as a prototyping method.

In the last 20 years, sand casting has evolved from being considered a "foundry man's art" to a data-driven science. It is now driving future shape technology to power the changing needs of the 21st century.

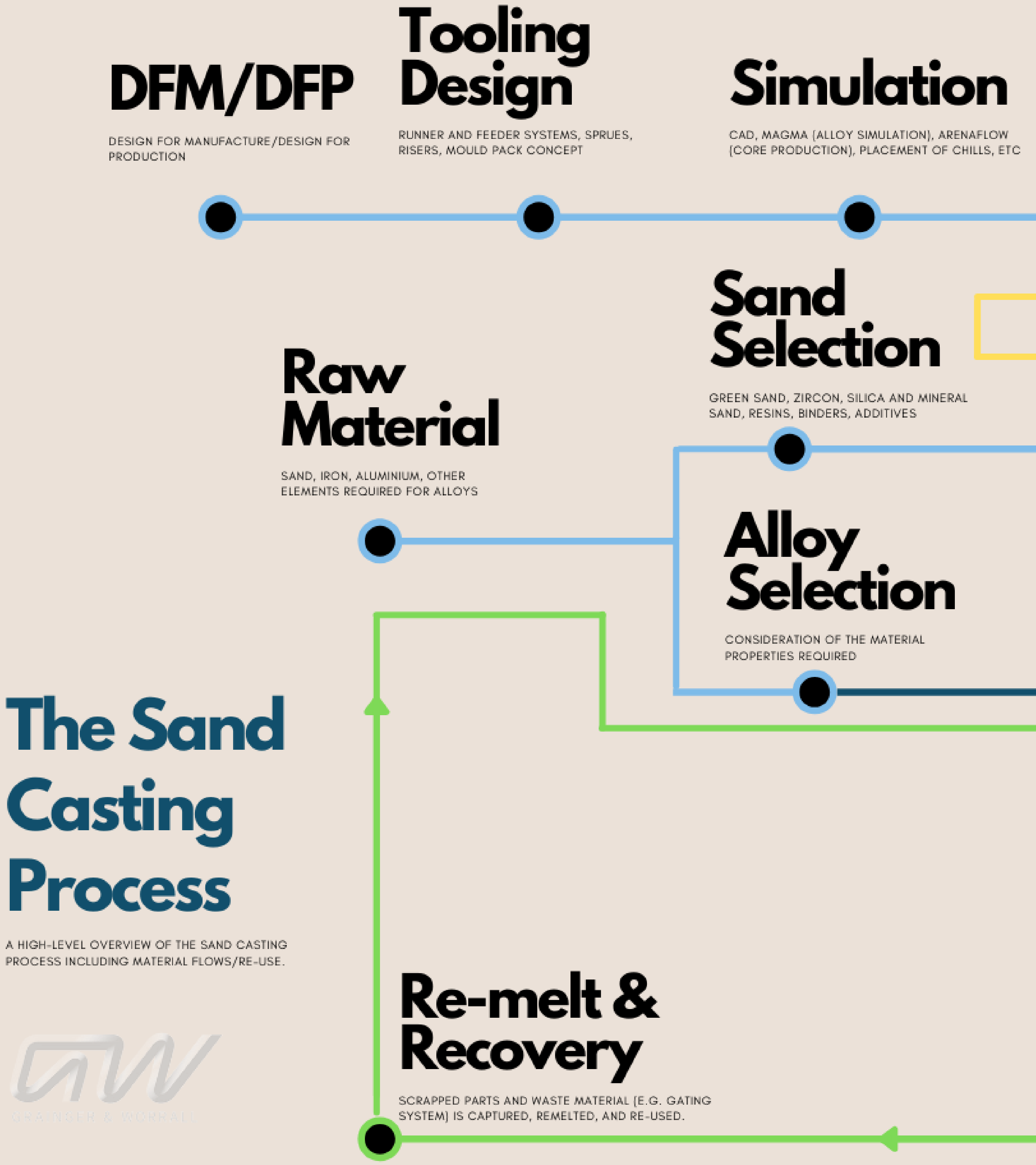
MATTHEW GRAINGER

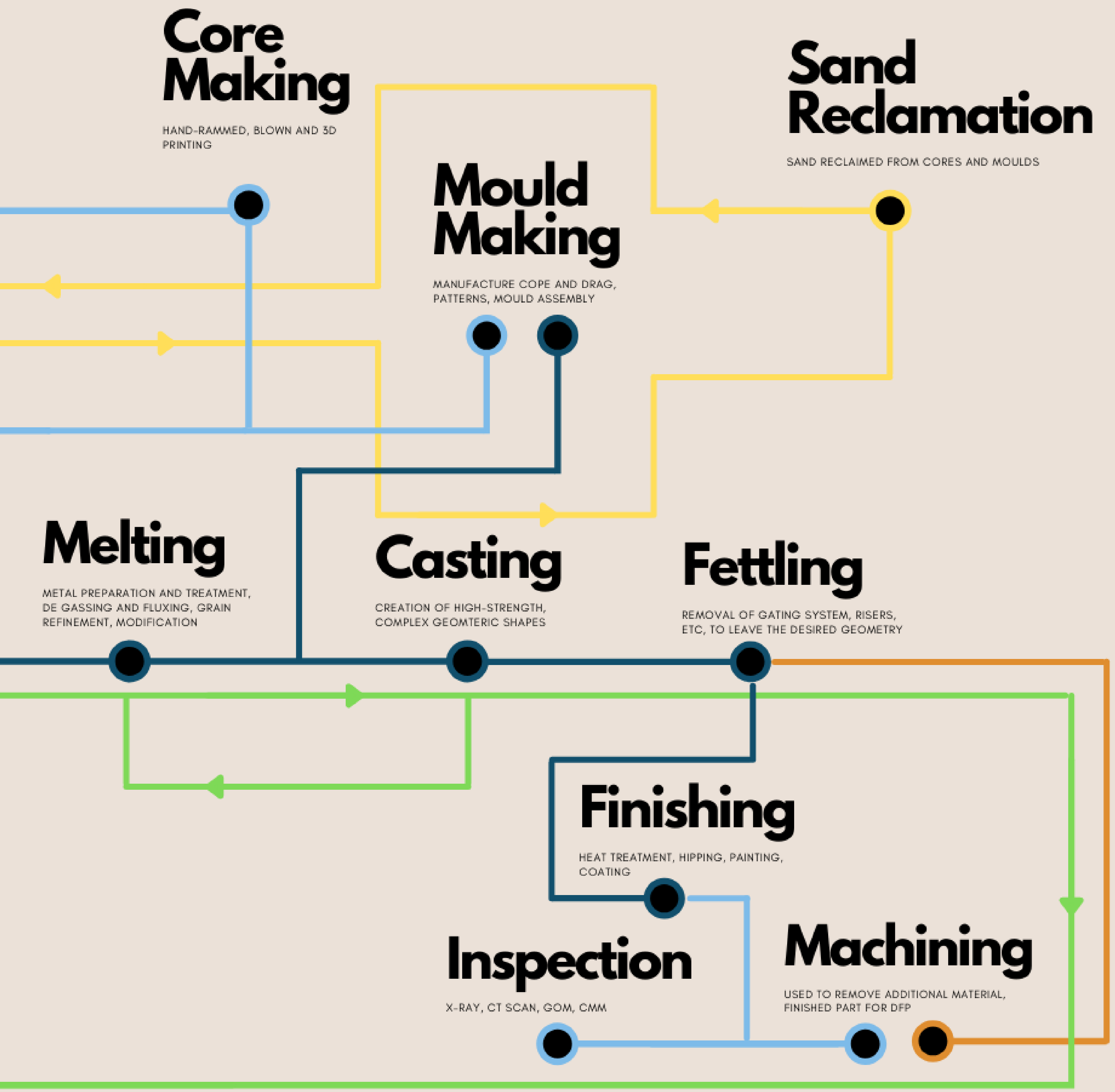
The Casting Process

AN ECO-FRIENDLY AND DATA-DRIVEN APPROACH TO MAKING CASTINGS

As well as being nearly 100% circular due to the recyclability of sand and metal used; sand casting can create complex geometries in a single part - vital for lightweighting and material reduction. Or put simply, sand casting allows us to reduce the weight of things that move and improve the efficiency of machines that use fuel. Both are essential for a greener future.

Data-driven simulations, tailored alloys, 3D sand printed cores, and the use of CT scanning to inspect the inside of parts, are all part of the modern sand casting foundry.





WHAT SHAPES CAN BE MADE?

Sand casting is suitable for complex and simple net shape forms, limited only by the pattern produced. The ability to cast large parts in a single piece provides opportunities for future automotive applications, allowing drastic part reduction and lightweighting. For an example, look at what Tesla has achieved with the Giga casting.

HOW QUICK IS THE PROCESS?

Additional finishing with machining is usually required after casting, but the lead times are short compared to other methods (any company supplying Formula 1 with just two weeks between races must be able to turn round design changes very quickly!).

WHAT APPLICATIONS IS IT USED FOR?

The flexibility of a manual assembly process and the fact that tooling board can be machined quickly mean that sand casting has a fast turnaround. This makes it suitable for low quantities- particularly prototyping and low volume series production.

ARE THERE ANY LIMITATIONS TO THIS PROCESS?

Old fashioned casting techniques used to cause porosity and mis-runs, but these are much reduced with today's simulation technology. The process is tremendously versatile. Consideration needs to be given to dimensional tolerancing and the ability to generate fine detail. Good method and process design is required to put the right material properties in the right places.

Design For Manufacture

IT'S ALL ABOUT STARTING WITH THE END IN MIND.

Working with your casting supplier at the DFM stage will help to identify ways to optimise the part design function, process used and material selection to achieve the desired properties for your casting and project goals.

Good casting design will optimise areas such as draft angles, split line placement, wall thinness and junctions in the part; ensuring design functionality is maintained while meeting specified material properties such as hardness, durability and ductility. Although it doesn't appear in the final part, the design of the runner and feeder system is critical too.

CAD software creates the 3D model and 2D drawings required to make it. **Magma** is a simulation package which models the flow and solidification of the metal, aiding the placement of chills and feeders to allow the engineer to maintain control of the solidification process. This minimises misruns and helps achieve the correct material properties (for example strength and hardness) in the finished part. **Arena Flow** simulates how the sand flows into a mould for blowing a core with a core blower.

Effective modelling can predict material properties and residual stresses that may impact part function. This is essential for material integrity and casting quality.

Questions to Ask Yourself

We get asked a lot of questions from customers regarding the casting design process. Here is a selection to consider...

HOW DOES THE PURPOSE OF THE PART IMPACT THE CASTING PROCESS?

Are you creating a MLP (Make Like Production) prototype to match production quality (with associated dimensional accuracy and replicated production properties)? Or do you just need a prototype of a shape quickly for testing purposes? The answer may influence your design considerations as well as the best process methods to optimise part function and properties. Some prototypes won't require methods that closely match production and final casting properties, whereas others will have to consider these much more carefully.

CAN I CHANGE THE PART DESIGN MIDWAY THROUGH THE PROCESS?

This is a common question! The various elements involved in sand casting have complex interdependencies, and accommodating design changes is a strength of the sand casting process (soft tools are easily modifiable and printed cores allow for quick changes). If the design is changed, we can then respond with new simulation and different runner feeder systems and chill placements.

HOW MANY PIECES OF SAND DO YOU NEED TO MAKE THE SHAPE FOR MY PART?

This depends on part complexity. While the piece count can be as few as 2, a recent complex gear box casting required up to 80 sand pieces. Sand piece count can be reduced by sand printing which allows separate cores to be combined.

Core Making

IT'S ALL ABOUT BEING ABLE TO MAKE COMPLEX SHAPES.

Cores are a vital part of the sand casting process, allowing design complexity by creating cavities and angles that would otherwise be impossible to be created from a pattern. Cores can also be necessary for the final function of the part. A great example of this is the water jacket inside an engine – cylinders could be machined in theory, but it's impossible to machine something inside that you can't even see with a CT scanner.

Making and placing sand cores accurately is crucial to the quality of the final casting. Cores must have high levels of permeability, be able to resist temperatures from the molten metal and have good hardness properties. Sand cores are designed to be broken down, or 'shaken out' at the end of the casting process with the rest of the sand mould.

Good core print location design is important and core media must be suitable to resist temperature and forces during the casting process. Good mould design takes into account how the mould is assembled too, resisting any movement of cores which can create a scrap part.

Different ways to make cores

HAND RAMMED

This involves manually ramming the cores using sand.

BLOWN

Created by shooting a sand / binder mixture into a tool cavity under pressure and cured with a gas.

3D PRINTED

3D sand printers can create tool-less cores rapidly with complex geometries. Multiple features can be combined into printed assemblies reducing sand piece count.

Key Insights/Questions

CAN CORES REDUCE A PART'S MATERIAL USAGE?

Well-placed and well-designed cores can help to reduce the weight of a final product, reducing the total amount of metal required.

Cores can be used to aid lightweighting by taking redundant material from component designs.

HOW IMPORTANT IS TYPE OF SAND IN CORES?

Sand strength is important. If this is below the pressure created by the liquid metal filling the mould, this could cause the core to split. Different sands have different properties including thermal expansion, density and heat capacity affecting dimensional outcomes and solidification rate. Core strength, permeability and outgassing need to be considered.

HOW FAST CAN 3D PRINTING PRODUCE CORES?

Instead of weeks with traditional blown cores, 3D sand printing can create a core in a matter of hours. This can speed up lead times significantly in the casting process. However, 3D printing is not suited for higher volume production.

WHAT IS THE BEST CORE PRODUCTION METHOD?

This depends on your part requirements and is influenced by factors such as volume, your lead time requirements and your budget. For example, 3D printing of cores is rapid, but expensive. Ask your supplier about potential hybrid core solutions too.

When to consider using 3D sand printing for cores

3D sand printing isn't only a rapid prototyping tool. It also offers the ability to print cores for sand casting. This can provide economic and design benefits to sand casting, including:

LEAD TIME BENEFIT

3D printing removes the need to create tooling for sand moulds, speeding up the process.

VOLUME

For lower volumes (particularly in prototyping), 3D printing can reduce investment cost, as well as the total project price.

GEOMETRY FREEDOM

As you don't need to be concerned with sand extraction from the tooling, or reassembly afterwards, 3D printing allows huge freedom in the geometrical complexity of parts that can be created. There is no need to consider draft angles and split lines.

FAST ITERATION

If a design has many iterations, 3D printed sand allows these to be created very easily and quickly. For example, water jackets in racing cylinder blocks.

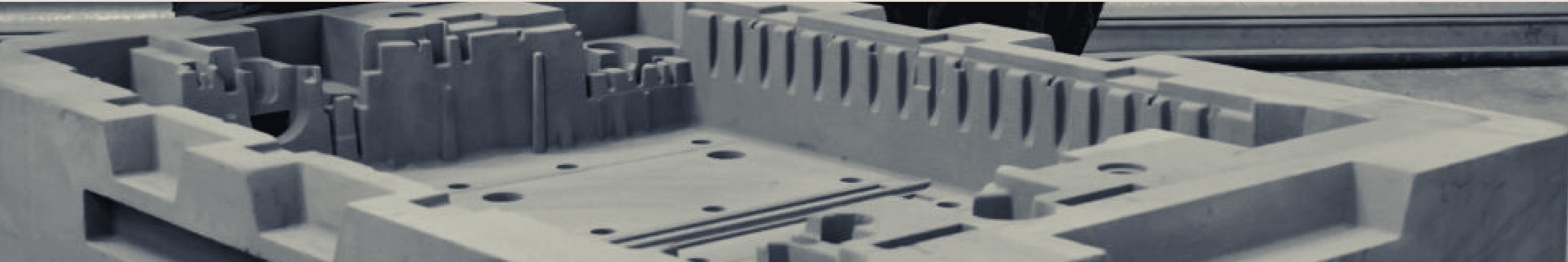
Mould Making

IT'S ALL ABOUT CREATING THE RIGHT CAVITY FOR THE METAL TO FILL.

Mould making creates the mould out of sand that will contain the molten metal. The mould is composed of two parts: a cope and a drag. To create the pattern, the pattern is filled with sand, and then removed.

Cores and gating systems (these allow the molten material to optimally flow through to the mould) are placed in the drag. The cope holds the sprue which is used to add the molten metal into the mould. To close the mould, the cope is put on top of the drag, then both parts are clamped together.

Choosing whether the mould should be printed, hybrid or fully tooled, as well as if it needs to accommodate chills is determined by what you require from your part or prototype. Some processes aren't replicable for production. For example, some processes and moulds will be suited to high complexity/high value products, and some won't - it depends what outcomes you require.



Questions to consider

WHAT TYPE OF SAND SHOULD THE MOULD BE MADE FROM?

A variety of sand types can be used, allowing designers and engineers to meet specified requirements for grain size, surface finish and rate of solidification required for part functionality. Sand types include silica, mineral sand and zircon sand.

DOES SAND TYPE REALLY MAKE A DIFFERENCE TO THE CASTING SURFACE FINISH?

Yes. Different sand types impact cost, as well as properties for strength and recyclability. **Grain size** also has an impact, and is distinct from sand type. The average sand grain is 180 – 200 microns. Different grain sizes create different properties for the part. A finer sand grain delivers a smoother surface finish as the grains can be packed more tightly together. However, a smooth surface finish can also be less permeable, risking gas entrainment and part distortion. Internal features can benefit from having a coarser, more permeable finish which allows gas to be removed from the core. Here a sand with larger grain size would be more suitable.

CAN MOULDS INCLUDE OTHER MATERIALS?

Moulds can also include other materials, for example steel, ceramic, iron or copper chills to enhance solidification rates and the mechanical properties of the part. This highlights the flexibility of the sand casting process to optimise for design function and casting quality at almost every stage.

Alloys

IT'S ALL ABOUT CONTROLLING MECHANICAL AND MATERIAL PROPERTIES.

The choice of alloy used in casting will determine the casting quality and material properties of the part, as well as the design functionality. Often, material selection reverts to what's always been used, but higher performing, specially created alloys offer high performance combined with cost efficiency.

Alloy selection will impact material properties such as corrosion resistance, thermal conductivity, hardness and how the metal will behave at high temperatures (whether it does or does not contain silicon).

Selecting the alloy will depend on the type of prototype part you require and how closely you need to replicate production processes (and material properties of the part) with a prototype.

WHAT IMPACT DOES MATERIAL CHOICE HAVE ON THE PROPERTIES OF THE FINAL CASTING?

The different properties of alloys will affect the properties of your part. For example, aluminium-silicon has high corrosion resistance compared an aluminium-copper alloy; but lower fatigue properties. Take a look at the table opposite for more information.

CAN ALLOY BEHAVIOUR BE MODELLED?

Yes. Magma has been refined over many years by comparing empirical results with predictions for different alloys and the parameters. As a result, the simulation can demonstrate the different results that can be achieved with different alloys.

CHARACTERISTICS	ALUMINIUM-SILICON	ALUMINIUM-SILICON-COPPER	ALUMINIUM-COPPER
STRENGTH	✓✓	✓✓	✓✓✓
DUCTILITY	✓✓✓	✓	✓✓✓
CORROSION RESISTANCE	✓✓✓	✓✓	✓
HIGH TEMPERATURE STRENGTH	✓	✓✓	✓✓✓
DENSITY (TYPICAL) G/CM^3	2.65	2.7	2.85
FATIGUE	✓✓	✓✓✓	✓✓✓
CONDUCTIVITY	✓✓✓	✓✓	✓✓
CASTABILITY	✓✓✓	✓✓	✓✓

THE CASTING PROCESS

The initial DFM stage sets the stage for tooling, pattern making and mould manufacturing. Material selection with regards to sand and metal alloys also have a significant influence on the mechanical properties of the casting. Metal pouring and solidification rates need to be controlled to ensure process repeatability and casting integrity.

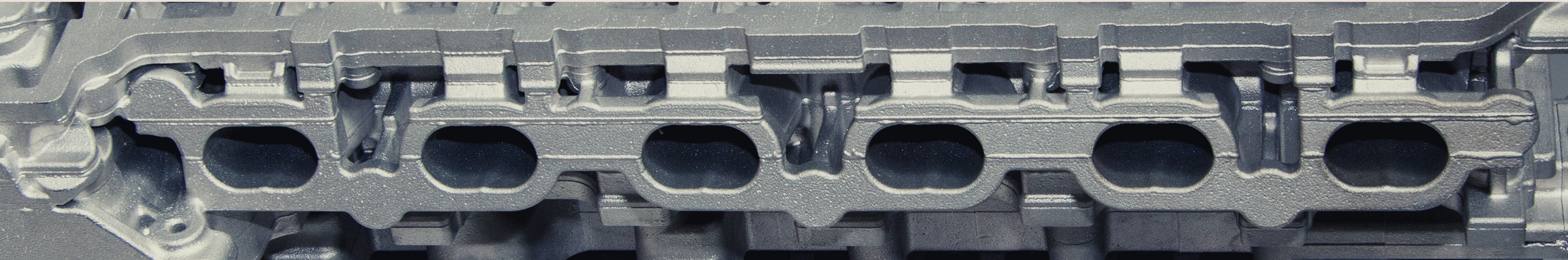
Casting

IT'S ALL ABOUT CONTROLLING THE RATE OF SOLIDIFICATION.

This is the point that all of the previous process steps converge and you finally get to make your part. But it's not as straightforward as just pouring the metal into the mould – there's quite a bit to think about. Controlling the rate of solidification is vital to achieve a quality casting.

A good foundry will ensure that the furnace is kept clean to stop any impurities contaminating the casting. The understanding of the technical aspects of sand casting now allows us to fine tune factors such as hydrogen content. The furnace needs to be degassed to control the quality of aluminium as it will react with hydrogen present. Degassing can be combined with flux treatments.

Temperature is important. It's vital that the temperature isn't too high to boil off some of the alloying metals in the aluminium. Maintaining temperature also confers repeatability benefits. Temperature is also critical because we have modelled a very precise solidification behaviour to get the right product, and this will have assumed a particular starting temperature. If this isn't met then the final part won't reflect what the designer intended, potentially causing scrap or out of tolerance material properties.



"Pouring a good casting is like pouring a good Guinness; it's all about getting the flow rate right"

MATTHEW GRAINGER - CEO, GRAINGER & WORRALL

Key Insights/Questions

WHAT IS THE IMPACT OF SOLIDIFICATION RATES?

Solidification rates are important in aluminium castings, with faster solidification improving the quality and material properties in specific areas of the part.

Accelerating the solidification rate will produce desired higher mechanical properties by altering grain size.

HOW ARE SOLIDIFICATION RATES CONTROLLED?

Solidification rates can be influenced by the addition and placement of chills in the mould and feeder positioning. The thermal conductivity properties of the sand type chosen also has an impact. For example, Zircon sand has higher thermal conductivity than other sand types- cooling the entire casting down faster.

HOW DOES CASTING METHOD DESIGN IMPACT THE PART?

Good casting method design reduces potential defects such as oxides in the metal, inclusions, porosity and cavities.

Optimising metal flow with good mould pack design reduces potential resistance in the mould. This includes radii on internal features to avoid turbulence.

WHAT PROBLEMS ARE CAUSED BY TURBULENCE?

Low turbulence runner feeder systems are vital to achieving a quality casting, helping to control the rate at which metal is poured into the mould. This decreases porosity by reducing gas entrainment. Porosity is linked to lower strength, and is often only found if the part is X-rayed, CT scanned or when machining surfaces of the part.

Finishing

Once the casting has cooled and solidified it needs to be demoulded and undergo a process of removing all the runners, risers, and excess material before it undergoes additional treatments. These processes are grouped together under finishing. The excess material can often be re-used in future castings – minimising waste and cost to support a circular economy.

KNOCK OUT

The casting needs to be removed from the mould. This can be done either by thermal knockout, or by using mechanical processes such as a rattler.

BANDSAWING

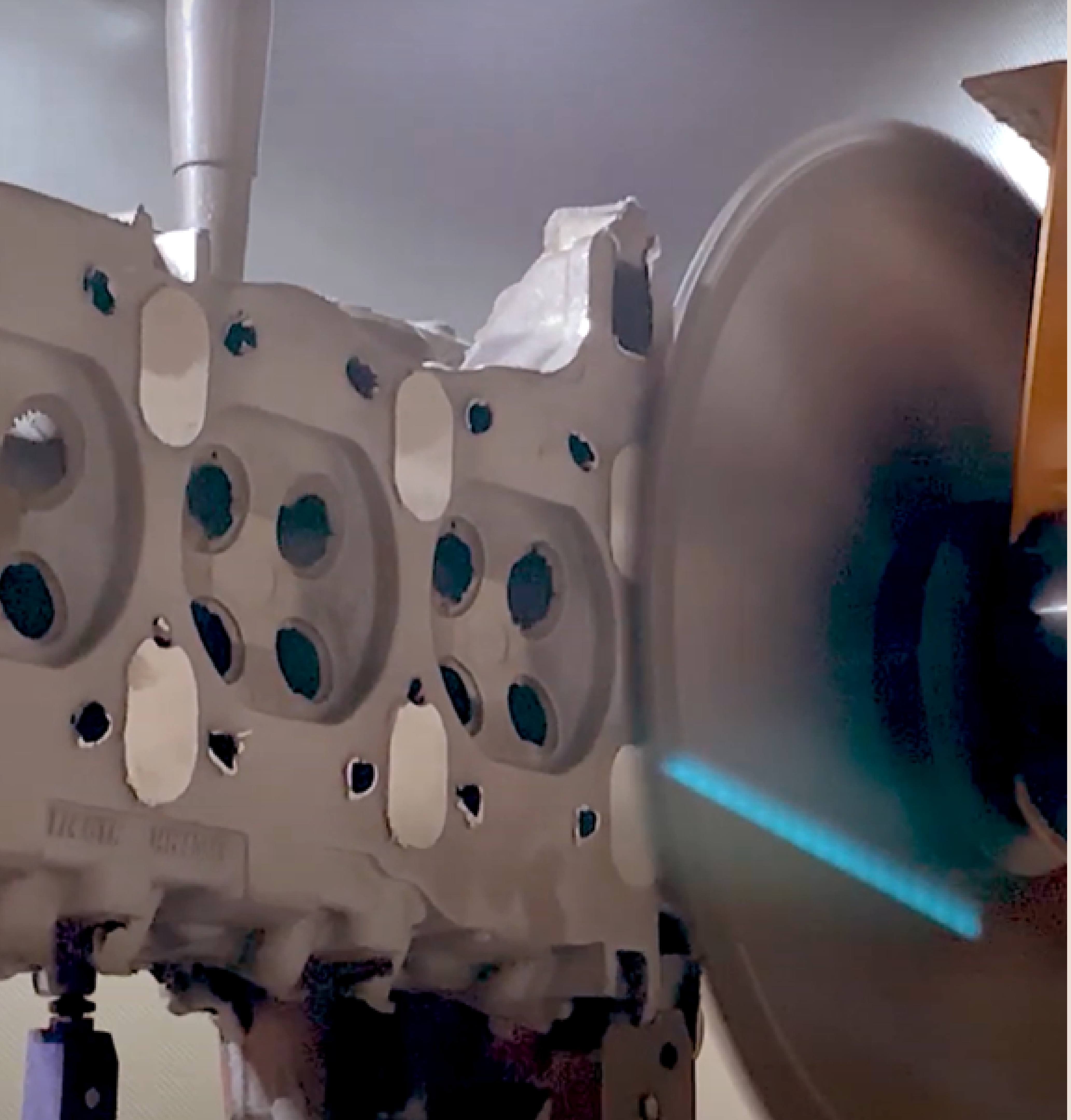
This removes the runner system and feeders from the casting. It can also be robotised when the volume is justified.

FETTLING

Fettling removes flash and other extraneous material not part of the final product. This can be done with hand tools for smaller volumes, or robots for production volumes.

SHOT BLAST

Used to give the casting a more uniform appearance and remove any burrs. Further surface finish treatments are usually applied such as powder coating, painting, or machining.



AN OVERVIEW

Post Processing

IT'S ALL ABOUT GIVING THE PART ITS FINAL MECHANICAL PROPERTIES.

What post processing options are available?

There are a number of different post processing options available to further modify the properties of the casting. Physical processing options can be used to change the shape/surface finish, chemical processes can include painting or surface treatments. Heat and pressure treatments can be used to change casting mechanical properties.

HIP'ING

HIP'ing can make a good casting great, but it can't make a bad casting good. It involves heating the casting, under pressure in the presence of an inert gas (usually Argon). This helps remove porosity from the casting, improves mechanical properties, and offers a lower cost route to high performance castings.

HEAT TREATMENT

Used on aluminium castings to modify the mechanical properties to balance tensile strength and ductility. Understanding how different temperature and exposure times influence the mechanical properties of the casting is key to getting the desired outcome.

IMPREGNATION

Where micro porosity and micro voids are a possibility (or have been identified via inspection), impregnation protects against the chance of the casting leaking air or fluids. It's a thermosetting plastic that seals against potential leak paths.

SURFACE TREATMENTS

Treatments such as painting, electrolysis and chemical coating can all be used to give a casting enhanced surface properties. This will usually happen after the casting has been machined (if this is required). The use of these techniques will be driven by the alloy composition of the casting, application and desired surface properties.

Key Insights/Questions

WHAT ARE THE BENEFITS OF HIP'ING FOR ALUMINIUM CASTINGS?

HIP'ing has a number of benefits, including potentially removing micro porosities, reducing impact of wear and corrosion and improving the mechanical properties of part. HIP'ing also increases the reliability and 'part life' of a component, helping to make parts longer lasting by improving fatigue resistance.

HOW DOES HEAT TREATMENT IMPROVE MATERIAL PROPERTIES?

Heat treatment can change the structural properties of the metal by redistributing material precipitated from grain boundaries to homogenise the microstructure. This balances tensile strength and ductility. Heat treatments can also change and improve other material properties such as corrosion or electrical resistance.

HOW DOES IMPREGNATION INCREASE CASTING INTEGRITY?

Impregnation helps maintain function of the part with sealing, reducing both internal corrosion and moisture. This ensures parts and components are pressure and leak tight, helping to remove potential leak paths.

DOES MY PART NEED POWDER COATING?

Painting, or powder coating is one of the most common surface treatments. This requirement will be determined by the specification, and can be used for aesthetic reasons or to enhance corrosion resistance.

Machining

IT'S ALL ABOUT ACHIEVING THE TOLERANCES OF THE FINISHED PART.

In order to get a casting into its final state it will almost certainly need to be machined. Machining offers a much finer degree of control over part dimensions and surface finish. This can include areas of the casting which join with other components, or have specific performance requirements. For instance, features such as mating surfaces and tapped holes will need to be machined.

For tight tolerance dimensions on a finished part, any casting process requires additional CNC machining after fettling or any heat treatments have been completed. It's important to consider machining requirements early on in the sand casting process, including the need for pick up points and datums. Specialist tooling may also be required depending on the part topology. This may have a significant impact on lead time and cost.

To get a better understanding of things to consider when it comes to machining, read our "**Machining Buyer's Guide**".

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Key Insights/Questions

DOES THE SURFACE SMOOTHNESS REALLY MATTER?

While surface smoothness can certainly be an aesthetic feature – it can also be important final for optimal part functionality (for example, for a sealing face). Surface finish can impact part function, including corrosion resistance, friction, fatigue resistance and strength. Considering these properties at the design stage is important.

HOW DOES MACHINING AFFECT LEAD TIME?

Machining processes can add significantly to lead time and cost. There are ways to reduce machining impact on lead times, if these are taken into consideration at the start of the casting process. These can include set up times, tolerance specification, temperature control and casting design (considering pick up points and datums).

CAN MACHINING MAKE THINGS THAT CASTING CAN'T?

Machining is used to create features on a casting with tight tolerances (often measured in microns), surface finishes or to achieve design dimensions that would be impossible to produce using casting alone.

DO I NEED TO MAKE ALLOWANCES FOR MACHINING?

A machining allowance is needed at the design stage to ensure the casting can be machined back to the specified tolerance. This depends on factors including casting size, material used and production volume. Balancing is also important. This is where critical features on the cast part are prioritised for measurement to balance the casting.

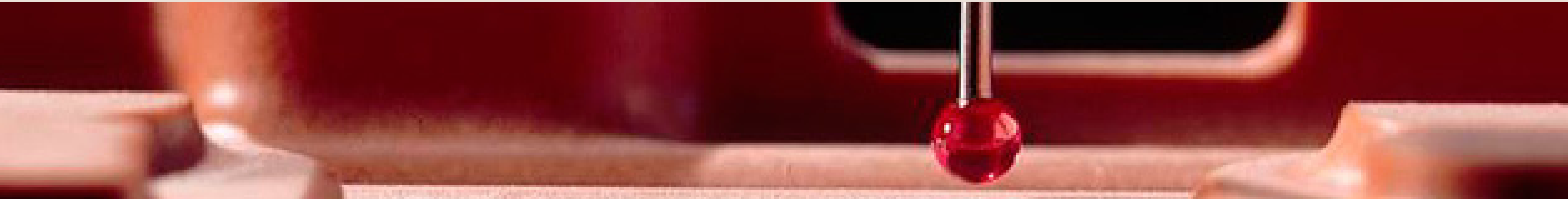
Inspection

IT'S ALL ABOUT MAKING SURE THE PART MEETS SPECIFICATION

Inspection and validation is a vital part of determining or demonstrating compliance, identifying any defects in the casting and generating inspection reports.

Visual inspection (sometimes including endoscope inspection) and tactile measurement can be used as a first pass when looking to establish part conformity or characterisation. More advanced technology such as CT scanning, X-ray, and GOM are used as non-destructive testing methods. Other inspection methods include crack testing, dye penetration, and mechanical property testing. All of these methods help ensure castings achieve optimal part function, meeting specifications for tolerance, surface finish, quality and dimensional accuracy.

The results of the inspection can also be used to balance the casting, which is a process needed before machining to ensure the casting 'cleans up'.



Questions to Ask Yourself

IS YOUR ACCEPTANCE CRITERIA FAIR FOR THE PROCESS?

All processes have a capability, within which certain tolerances can be met with a high degree of probability (measured by Cpk). If you specify dimensions or properties tighter than this capability, then more parts will be out of specification (defects). These will require rework, concession or scrap. There are so many factors that affect process capability that it is important to discuss this early on in the design process - especially for critical features.

DO YOU UNDERSTAND THE ACCEPTANCE CRITERIA SPECIFIED?

Some features on drawings have tolerances inherited from earlier designs or are perceived 'rules of thumb' and not necessarily deliberate choices made by the designer. This is worth checking carefully. Over-toleranced features can cause the designer to build-in unnecessary cost which can be significant. If not challenged then unexpectedly high scrap rates could jeopardise production capacity.

HOW SMALL A DEFECT CAN YOU FIND WITH A CT SCANNER?

CT is an X-ray machine with the ability to generate a 3D Grayscale model. The 3D pixels are called voxels. With detection sensitivities around 2% of section thickness, a defect of 0.2mm is detectable in a plate of 10mm thickness. The limit of resolution is 1 voxel- around 0.1mm.

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