Vacuum Induction Melting Process Optimization in Precision Investment Casting Furnaces

Abstract

The alloy vacuum induction melting process is one of the most critical events in the Vacuum Precision Investment Casting (VPIC) furnace, and also in the Investment Casting Process.

The induction melting process is concerned with how solid alloy is induction melted in preparation for pouring into a preheated shell mold. It is the first point for a successful and defect free casting process. It begins with the ingot and refractory one-shot liner loading stage into the induction coil, then continues with the power input from the VIP® source into that coil, which finally melts the solid ingot by means of induction. Once alloy is melted, process continues with the melt dross evaluation witnessing the cleanliness of the alloy, and it finishes with temperature regulation of the metal to have it ready to be poured into the shell mold.

This work will summarize features and recommendations around the design of the VIP®, induction coil, ingot/liner charging system, melting recipe and final temperature regulation systems, as key parameters and their effective management and control. Additionally, some best practices will be discussed to enable investment casters to have a fast, accurate, consistent, reliable and clean melting processes.

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**Introduction**

The vacuum induction melting process of the alloy to be cast is a critical stage within the Vacuum Precision Investment Casting (VPIC) furnace.

How solid alloy is induction melted in preparation for pouring into a preheated shell mold is the basic background of this process. An effectively controlled melting process provides a solid foundation for the investment caster to achieve the demanding quality requirements of a modern high-class precision casting foundry.

This paper includes recommendations and best practices around the design of the induction power supply (VIP®), induction coil, alloy, ingot/liner charging system, melting recipe and final temperature measurement systems, camera and view ports, identifying key parameters and their effective management and control.

The paper also indicates the basic features, best practices and technicalities of the vacuum melting with the three key process objectives: productivity, quality and consistency.

All best practices shown are applicable for both Equiaxial or Directional Solidification-Single Crystal (DSSX) process technologies.

![Picture showing vacuum melted alloy being poured into a shell mould.](image)

*Figure 1.* Picture showing vacuum melted alloy being poured into a shell mould.
Melting Process Goals

Three different aims can be identified in the vacuum induction melting process for investment casting processing. Each is sufficiently critical to be analysed below:

1. **Quality**: means having a robust chemistry control and maintaining a clean melt ready to be poured into the shell mold. The target quality can be detailed in two different objectives:
   a. *Metallurgy*: the melting process should not impact negatively the chemistry of the alloy, such that the chemical composition should not be modified negatively by the melting process. Changes in the chemistry may produce a non-compliance of the strict specifications of the customers, as well as risk of producing metallurgical defects in the final castings.
   b. *Liner/crucible integrity*: the melting process should prevent any damage or breakage of the liner/crucible, through both heating and melting stages. A breakage of the liner/crucible incurs a direct cost for the alloy and liner/crucible, and also a loss in production having the furnace down while it is recovered. Damage to liner/crucible could also produce a risk of having metallurgical defects in the final castings.

2. **Consistency**: the strict requirement to always follow the same melting process cycle to cycle. The 3 different major sources of changes in the process:
   a. *Human Factor*: there is a need to avoid variation created by different operators, or, at least, keeping this variation to the absolute minimum.
   b. *Material*: prevent any factors related to the change of alloy materials, sourced from different vendors, or to manage variation from the same vendor.
   c. *Machine*: monitoring and avoidance of any deleterious machine effect due to its incorrect behaviour during melting processes.

3. **Productivity**: as the ability to conduct the melting process as fast as possible to maintain short cycle times, and enable the production of as many castings as possible, thus reducing the unit cost. This is especially applicable to equiax casting where this process cycle time is shorter, and the melting time represents a bigger percentage in total process time.

![Induction Coil Unit](image-url)
Melting Main Steps

The following flowchart shows the equiaxial process and indicates materials and processes involved:

![Equiaxial vacuum precision investment casting process flowchart](image)

*Figure 3. Equiaxial vacuum precision investment casting process flowchart. [1][2][3][4]*

The chart above explains how the process starts quite close to the VPIC furnace with the shell mold input from the shell room process. This shell mold traditionally undertakes a mold wrapping process where the mold is thermally insulated with ceramic fibre blanket. This insulation prevents heat loss during the transfer of the shell mold into the VPIC. It also helps controlling how the casting solidifies after pouring process. Once the shell mold is wrapped, it is loaded into the mold preheating furnace where it is preheated in preparation for casting.

Subsequently, the ingot and liner materials are loaded into the VPIC furnace, and melting can occur after which the melted alloy is ready to be poured into the shell mold. In that moment, the preheated shell mold is taken out from the preheating furnace and quickly moved into the VPIC furnace, known as mold transfer in stage. Once the preheated shell mold is ready in the pouring position, the pouring stage occurs, where the melt alloy is poured into the shell mold. Finally, the shell mold is removed from the furnace back to the initial loading position, which is known as mold transfer out process.
In the case of DSSX casting process, the following flowchart represents the process:

![Flowchart of DSSX casting process](image)

**Figure 4. DSSX vacuum precision investment casting process flowchart. [2][3]**

As it can be witnessed in the previous flowchart, in the DSSX process, shell mold follows similar wrapping and preheating steps to the equiaxial process, however typically preheated to a lower temperature as it shall be heated later inside the VPIC furnace. The shell mold is then moved into the VPIC furnace, moved to the heating-pouring position, and mold heating stage starts. Once heating is complete, or it is about to finish, ingot melting process begins (with the liner and ingot loaded previously). Once alloy is melted and conditioned to be poured, the pouring process occurs. Subsequently, the mold undergoes a slow highly controlled withdrawal process out of the base of the heater. Finally, once complete, mold transfer out is carried out.

This is the specific flowchart for the melting process:

![Flowchart of alloy melting process](image)

**Figure 5. Alloy specific flowchart details.**

The previous figure explains the specific process around melting. It begins with material charge: the alloy and the refractory used to hold the alloy (liner). Once they are both loaded, melting happens by means of induction melting. Once alloy is fully melted, temperature measurement is done (this may start from solid state if desired), and subsequently dross evaluation is carried out to make sure that the alloy is clean enough to be poured into the shell mold. Finally, the process finishes with the temperature regulation to the desired pouring temperature, which means that the alloy is ready to be poured.
Melting Main Key Elements

The image below indicates the key elements considered in the melting process shown on a Consarc VPIC furnace:

![Image of Consarc VPIC furnace with labeled key elements]

**Figure 6. Melting related main key elements shown in a Consarc VPIC furnace.**

The key elements to be considered in the melting process include:

1. Induction Power Supply (VIP®).
2. Induction Melting Coil.
3. Ingot.
4. Liner/Crucible.
5. Ingot/Liner Loading Stage.
7. Cameras and Viewports.
8. Vacuum System.
9. Melting Procedure
The following paragraphs detail each of the all key elements listed above:

1. **Induction Power Supply (VIP®):** the Inductotherm VIP® is a voltage fed designed unit that converts multi-phase line voltage into a single-phase variable frequency current injected into the induction coil.[5]
   - The power supply creates the power needed to melt the alloy by means of an induction field that is generated within the induction melting coil.
   - The power and frequency are selected in the design stage to ensure effective matching with the desired load to be melted.
     - The power directly heats metal inside the induction coil, and it is sized depending on the melting rate and total charge to be processed.
     - The frequency is calculated to achieve the best coupling and stirring effect. Consarc offers multifrequency VIP® designs based on the customer charge demands.
   - Effective matching of the VIP® unit, allows the quickest, and most reliable-efficient and accurate melting process:

The following chart shows a chart that gives the best frequency value for each coreless induction furnace size.

![Furnace size vs. Frequency for Coreless Induction Furnaces](image)

*Figure 7. Chart showing Furnace Size vs Frequency for Coreless Induction Furnaces [5]*

The following pictures show VIP® units in the version of SCR used as inverters, and VIP®-I which use IGBT technology:
2. **Induction Melting Coil**: contains the liner/crucible rammed inside it. The melting process happens in the coil due to the coupling of the magnetic induction fields created with ingot inside the liner/crucible, heating it until it completely melts. The coil is connected to the VIP® through the water-cooled power leads.
   - The size of the coil and the number of turns is calculated by the maximum and minimum alloy capacity to be melted.
   - If the melting range is large, the best solution is to have different size coils and exchange them when required.

Consarc enables easy and safe coil changes due to elimination of flexible hoses inside the furnace and making coil-lead connections outside of the vacuum furnace.

3. **Ingot**: is the material/alloy to be melted and then poured into the shell mold:
   - The target should be to maximize the ingot size within the liner/crucible internal diameter for optimum induction coupling, and therefore, fastest melting.
Single ingot loading is preferable to multiple ingots. If multiple ingots are used, the smallest piece ingot should be loaded into the bottom of the liner.

A chamfered ingot base where in contact with the liner is always recommended for a safe contact with liner/crucible, preventing any scratching/inclusion formation.

Care to be taken when using ingots formed by a notch and fracture type process, due to presence of sharp edges.

Soft, accurate and careful loading is needed also to prevent scratching.

Both incoming ingot and final casting chemistry shall be controlled, to guarantee a good melting practice, so as to ensure that there is no impact on the chemistry caused by the melting process.

It is critical to make sure that the alloy ingot is clean before melting to prevent inclusions.

It is also very important to evaluate the cleanliness of the alloy when it is melted, known as dross evaluation.

![Figure 10. Picture of chamfered ingots.[6]](image)

4. **Liner/crucible:** is the refractory receptacle that holds the alloy during the melting process until pouring is complete. There is a growing trend in the investment casting industry for the use of one-shot liners instead of crucibles. One-shot liners are preferable due to their quality advantage against single rammed crucibles, as they ensure the use of new refractory for every melt, preventing any issues caused by worn crucibles or material contamination / dross carry over for one melt to another.

- Material selection is a key factor to prevent or minimize reaction between the alloy and the refractory:
  - Fused silica. Most standard and cheapest type.
  - Alumina and Zirconia. Recommendable for reactive alloys.

- Drying of liner before its use is recommended to improve yield.
- Liner size shall meet the charge requirements guaranteeing an appropriate fill level.
- Backup crucible shall have minimum 13mm gap inside the coil to allow ramming properly.
It is critical to understand the interactions that may happen during the alloy and refractory during melting process. The following figure includes a diagram showing those interactions in detail by defining three different areas: above the melting line, on the melting line and below melting line:

As it can be seen in the figure above, up to 12 different reactions may occur in the interaction between the alloy, refractory and atmosphere during the melting process. Therefore, it is evident this is a rather complex process to control. There are 3 rules to follow:

1. Choose the best refractory depending the alloy and conditions of melting.
2. Melt and hold the alloy at the lowest possible temperature.
3. Hold alloy in the refractory the shortest time possible.

5. **Ingot/Liner loading stage**: the method used to load and unload liners, and also alloy. Soft loading is always required to avoid scratching and liner damage, and for this reason, horizontal loaders are often preferable to vertical loaders. Approximate limits for each type of charging systems:
   - Vertical loading systems for large charge capacities approx. ≥150 kg.
   - Horizontal loaders for smaller charge capacities approx. ≤150 kg.
In addition, Consarc offers liner disposal systems for rapid liner removal, saving process cycle time.

6. **Temperature measuring devices**: there are two technologies available to measure melt temperature: Optical Pyrometry and Immersion Thermocouples:
   - Optical pyrometers allow for continuous melt temperature measuring:
     - External sight glass with isolation valve protection to allow periodic cleaning by the operator.
     - Argon bleed with mass flow control to prevent condensation onto the pyrometer sight glass coming from the melt. Mass flow control systems to provide an accurate and controlled method to measure the quantity of argon used.
     - Alloy emissivity/slope correction factor (also in the recipe). This allows a precise adjustment of the reading of the pyrometer.
     - Automatic correlation/compensation to Immersion Thermocouple reading. This is a very useful tool to calibrate/adjust the pyrometer reading.
     - Dual pyrometer systems for a consistent process. Having two devices reading at the same time into the same melt point, producing a very reliable way of achieving right and accurate temperature readings.
     - Laser sighting/integrated camera option, that enables a precise adjustment of the point where the pyrometer focusses. Also, integrated camera enables to record melting process.
     - Air curtain system option, which prevents contamination with dust coming outside onto the external side of the pyrometer sight glass.
   - Immersion thermocouple devices for optical pyrometer discrete checking/calibration:
     - It is a contact process, very accurate, not affected by light, alloy type or emissivity changes and whose immersion can be easily automated.
     - There are two possible solutions:
       - Quick change type B, R, or S thermocouple probe.
• Multi-dip sheath design, single thermocouple or interchangeable designs of the same TC types.
  ▪ Trend towards less use of immersion thermocouple system because its potential contamination with use.

Figure 14. Picture of Consarc dual pyrometer system (left), and immersion TC measuring melt temperature.

7. **Cameras and Viewports**: provided to record/witness the melting process.
   - Cameras are recommended to witness the process and assure a consistent melting cycle. Also, they allow the operator to evaluate the dross level on the surface of the melt before pouring.
   - Viewports for the operators shall be located in appropriate positions to monitor the process properly and allow their reaction upon seeing an issue during melting.

Figure 15. Consarc camera arrangement on the left, and viewport in the right hand-side.

8. **Vacuum System**: to create the necessary inert atmosphere to prevent any oxidation of the alloy during melting, as well as harmful impurity element removal from the alloy, during melting. There are normally two groups of vacuum pumping systems installed in VPIC furnaces:
   - High vacuum system to achieve up to 10e-4 - 10e-5 mbar range or greater vacuum levels:
- Diffusion pumps offer high vacuum (~10e-4 – 10e-5 mbar range) during melting.
- Oil Vapour Boosters pumps offer high vacuum but lower than that of Diffusion pumps (~10e-3 mbar range), but a more stable vacuum during melting stage.

![Diffusion pumps and Oil Vapour Boosters pumps](image)

*Figure 16. Examples of high vacuum pumps: Diffusion (left) and oil vapour booster (right). [10][11]*

- Low vacuum or roughing vacuum systems, based on mechanical and roots type pumps, achieve 10e-2 mbar vacuum ranges.

![Consarc roughing vacuum pumping system and dry vacuum mechanical pump](image)

*Figure 17. Consarc typical roughing vacuum pumping system arrangement (left), and dry vacuum mechanical pump (right). [12]*

There is an important need of avoiding too deep vacuum: alloy composition could be affected by vaporization of elements during melting. The following figure includes a table that shows some typical elements contained in superalloys, with the temperatures at which specific vapor pressure exists depending on the pressure level from 10e-3 torr to 760torr:
As it can be witnessed above, there are some elements which have quite low temperatures at which vapor pressure exists. The longer time at temperature and at the vacuum level, the greater the loss of the metallic elements by evaporation.

It is also critical to avoid leaks: leak up rate test is the key factor rather than vacuum level. Making dynamic tests rather than static tests is always preferable to ensure that there are not leaks or, at least, are controlled and acceptably low.

9. **Melting Procedure**: the specific procedure used for heating and melting the alloy. It is critical to always run an automatic melting recipe to have a consistent melting stage, for the following reasons:
   - Prevents human factor as the melting cycle runs automatically.
   - Regulation of power during the solid and liquid stages of melting to accommodate the different situations that melting process witnesses from heating starting until the melt is ready to pour.
   - Avoids metal splashes by the programmed reduction of power when necessary.
   - Targets repeatable total melting time/energy, which is important from the point of view of process control and energy cost saving.
   - Assures the same minimum metal-refractory interaction time avoiding undesirable inclusions.
   - Assures that the same thermal cycle is always conducted.

Additional process control features include:

- KPV data logging – the ability to record and subsequently analyse all Key Process Variable (KPV) data. This is a necessity for the lifetime data record required of certain industry sectors.
- Tracking Variables – the ability, in an automated manner, to create alarms for defined parameters that are out of tolerance through a cycle. The following figure includes a picture that shows a typical Consarc Human Machine Interface (HMI) screen for melting stage with several features and parameters for a good automation process:

![Consarc Typical Melting Recipe Management](image)

Figure 19. Consarc Typical Melting Recipe Management
These all factors explained above can be wrapped summarised up by a Fishbone diagram, grouping them as Material, Measurement, Machine, Method, Environment and Human Factors:

![Fishbone diagram](image)

*Figure 20. Melting Main Key Elements shown in a Fishbone diagram.*
Final Conclusions

The following conclusions can be made regarding an optimised Vacuum Induction Melting process applied to Vacuum Precision Investment Casting:

- The melting stage is one of the most critical activities in the Investment Casting Process.
- It is a key point for a successful and defect free casting process.
- It involves several important stages/activities to be controlled and optimised:
  - VIP® power unit and coil designs, to be matched and accommodate all the melting requirements (productivity and consistency).
  - Ingot preparation and sizing, to prevent scratching, and to have the best induction coupling during melting stage (quality and consistency).
  - Liner/Crucible material and shape selection, chosen to minimise control the melt-refractory reaction (quality and consistency).
  - Ingot and Liner/Crucible loading, to have the fast and reliable charge (consistency and productivity).
  - Melting witnessing/controlling with viewports/cameras and optical pyrometer and immersion thermocouple systems, to have process control (quality and consistency).
  - Vacuum system, to protect the alloy from oxidation and accurate chemical control (quality and consistency).
  - Appropriate melting procedure/automation/logging/control for an accurate, fast and consistent melting process (quality, consistency and productivity).
Cross References

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