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Vacuum cap (VCAP) technology for enhanced material properties in advanced air casting applications

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Air melting processes can suffer from limited control of alloy cleanliness composition. Oxygen and nitrogen levels change from heat to heat, and the current practice to decrease them is to add virgin material because deoxidation with only aluminum could cause non-metallic inclusions. Low vapor pressure tramp elements like Pb, Bi, Zn, etc. are reduced via dilution. The reduction of carbon is also a metallurgical challenge in air melts.
VCAP furnaces are a hybrid of air induction and vacuum refining capability. Once the main charge is melted in air, a vacuum cap is applied that can produce a significant degassing effect for reduced casting defects, removal of tramp elements and decarburization.
Our results from research and production units will show improved mechanical properties and better micro-cleanliness. We present the main features of the VCAP technology as a recommended technique to obtain enhanced material properties and a more reliable air casting process.

KEYWORDS: VCAP, AIR MELTING, VACUUM MELTING, DEOXIDATION, DECARBURIZATION, TRAMP ELEMENTS

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INTRODUCTION

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

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

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

Fig.1 - 2.5t VCAP furnace.

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

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

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

The position and application of the main specialty melting processes for High Performance Alloys (HPA) is best illustrated in a flow diagram. Figure 3 shows the principal production methods for wrought and cast premium quality intermediate products.

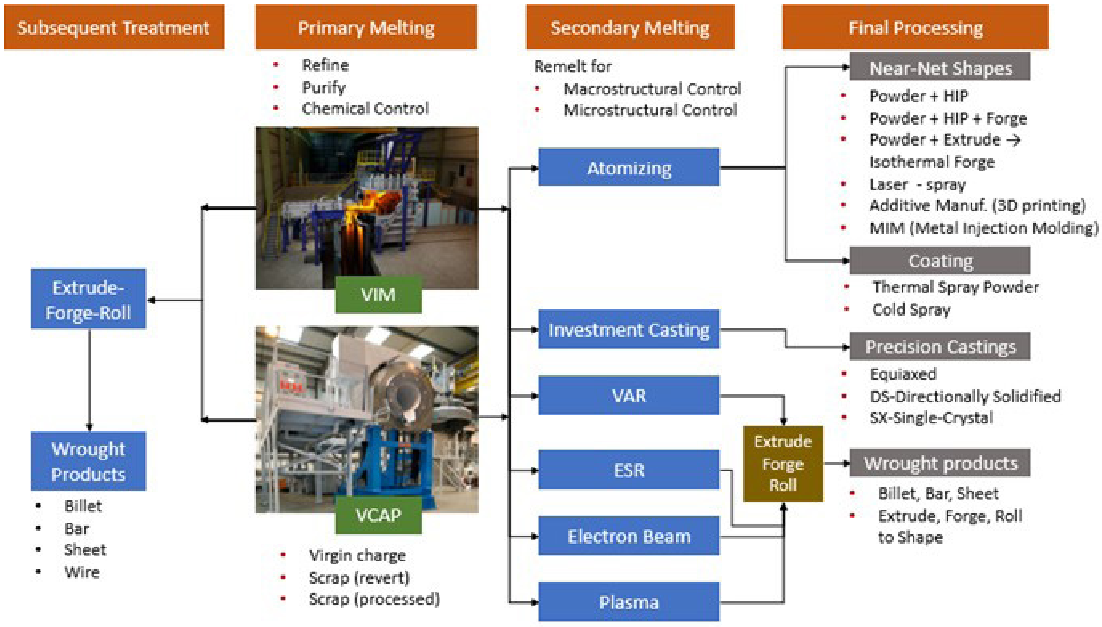


Fig.3 - Potential processing routes for products cast from vacuum induction melting (VIM) or VCAP ingots or electrodes. [6]

The primary melting products become the feedstock for subsequent secondary melting processes to produce the intermediate and final product forms for thermomechanical processing, powder consolidation work or investment casting.

VCAP main highlights

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

- It is available in a wide size range from 50kg to 20,000kg:
  - o This allows customers to choose furnaces sized for small pour weights or research purposes, and also for large pour weights.
- Vacuum levels ranged from 100mbar to 0.01mbar:
  - o This means pressure levels from low vacuum range close to atmospheric pressure, with or without argon partial pressure, to quite high vacuum levels.
  - o More precise chemistry control of the alloy.
  - o Vacuum levels highly depend on the C and O composition and following decarburization reaction.
- Argon partial pressure atmosphere melting also available.
- Argon/nitrogen porous plug systems are available for additional agitation inside the melt and then, promote good mixing, degassing and overall metallurgical reactions.
- Can be used to process almost all metals:
  - o It is available to melt and mix of selected raw materials / revert.
  - o Many different material types such as stainless steels including duplex and super duplex, austenitic stainless steels, carbon steels, nickel-molybdenum-chrome alloys, high speed tool steels, iron-nickel-chrome heat resistant alloys, iron-cobalt-chrome heat-resistant alloys, nickel superalloys, nickel copper alloys, nickel-cobalt alloys, pure copper, etc.
- Some different metallurgical processes may be achieved:
  - o Reduction of hydrogen, oxygen and nitrogen (vacuum degassing).
  - o Reduction of low vapour pressure tramp elements like Pb, Cd, Bi, Zn.
  - o Deoxidation using combination of vacuum and C-O reaction.
  - o Decarburization - intensified C-O reaction at low pressure enabling excellent decarburization for extra low carbon levels (improvement of alloy

workability/machinability).

o Desulphurisation (limited) – Use of reducing slags and / or powder injection in air or controlled atmosphere

- Better micro-cleanliness due to strong carbon deoxidation and smaller residual inclusions, and subsequent:

  o Increase of the fluidity of the metal, which improves filling of the mold.

  o Significant improvement of mechanical properties.

  o Improvement of technological characteristics like hot workability, weldability and machinability.

  o Significantly reduced scatter in product properties and characteristics, so less rejections.

MAIN APPLICATIONS

Overall, VCAP technology focuses on high-quality foundry applications that do not require complete vacuum melting, but where air melting does not produce good quality castings.

Here are some examples of VCAP specific applications:

- Investment Casting Foundries: higher-end air melt business.
- Nickel and super alloy melters: lower grade alloys not requiring VIM.
- Steel foundries.
- Steelmakers.
- Stainless steel melters: where VCAP shows better decarburization levels compared to AOD, and with much smaller size.
- Non-ferrous applications:
  o Copper.
  o Aluminium.
- Metal powder production plants.
- Others.

The following list summarizes some specific examples of materials processed by VCAP technology:

- Stainless steels including duplex and super duplex: ASTM Gr4A, Gr5A, Gr6A, EN 1.4517, 2507,
- Austenitic stainless steels: AISI 304.
- Carbon steels.
- Nickel-Molybdenum-Chrome alloys: Hastelloy B/C, Alloy 59.
- High speed tool steels: 1.3243.
- Iron-Nickel-Chrome heat resistant alloys: ASTM A297, ASTM A351/CF3/CF8 and its variations, EN 10283 GX4CrNi13-4.
- Iron-Cobalt-Chrome heat-resistant alloys: UmCo50.
- Nickel superalloys: Alloy 625, Hastelloy C22.
- Nickel steels: A352LC3.
- Nickel Copper alloys: Monel 500.
- Nickel-Cobalt alloys: MARAGING 350
- High purity Copper.

PROCESS STEPS

Essentially, VCAP process has 3 big steps that will be detailed below (also shown in the figure 4 below):

- **Atmosphere charging (cap OFF step)**

  This is with the chamber open to atmosphere

  1. The alloy is charged inside the melting furnace.

  2. Once the alloy is charged, the power is switched on and melting starts.

  3. When the alloy is fully melted, a first temperature reading is taken by using a hand immersion thermocouple.

- **Cap ON step**

  Induction power remains still on.

  4. The cap is moved into position over the furnace.

  5. Once the cap is in position, evacuation of the chamber starts.

  6. Once the target vacuum level is reached, flow of bottom porous plug is activated.

  7. Additional charges are made as required through an auxiliary chamber.

  8. Temperature is measured under vacuum (through an auxiliary chamber too), and melting power adjusted accordingly.

  9. Sample is taken to check the chemistry.

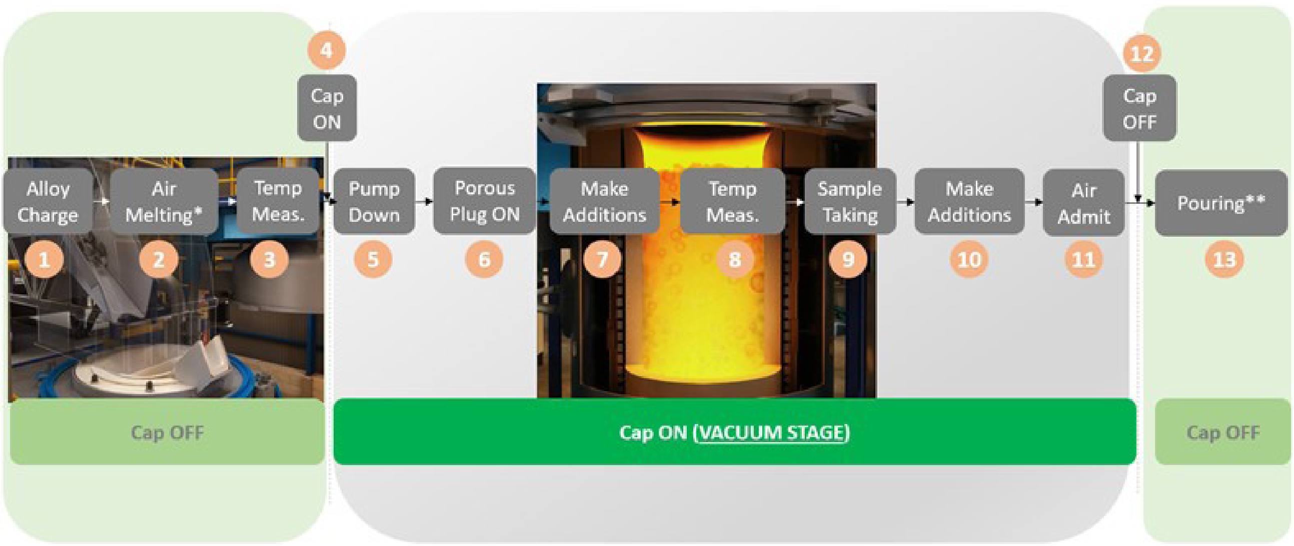
  10. Additions are done based on the chemistry obtained. Additional sampling for chemistry may be performed if necessary.

  11. Once the desired final values are obtained, the melting chamber is backfilled using gas (air, argon, nitrogen) as required.

- **Pouring/Tapping**

  12. The cap is removed again after the chamber is vented.

13. The final pouring is done. Eventually, there might be some final temperature measurements just before pouring to adjust the induction melting power.



*Melting might also be done under vacuum

**Pouring may be done with cap ON in specific VCAP furnaces.

Fig.4 - VCAP basic process flowchart.

Case study at Brno University of Technology

The following cases studies are within the partnership with Brno University of Technology. The VCAP furnace installed at Brno University is an 80kg melt size Consarc VCAP furnace as seen in figure 5.

The experiments are usually performed together with experimental calculations of activities based on the chemical composition and comparison of the results of the measured activities. It also approaches the evaluation of the microstructure or mechanical properties. For the department of Foundry Engineering at Brno University of Technology, students participate in research as part of their diploma thesis in order to gain practical experience in conducting and evaluating experiments. [4], [5].

The following table presents some examples of the benefits obtained from the VCAP technology tests. It includes different experiences with different alloys, and with different metallurgical objectives for each one of them:

Tab.1 - Summary of VCAP tests performed.

N.	Size (kg)	Alloy	Initial value	Final value	% of reduc.	Comments
1	80	1.3243 Tool Steel	nitrogen 426ppm	nitrogen 62ppm	85 / 43	Degassing
2	80	ASTM A297 HL-Al Steel	oxygen 56ppm	oxygen 32ppm	47	Degassing
3	80	ASTM A297 HP-Al Steel	nitrogen 1932ppm	nitrogen 1029ppm	49	Degassing
4	80	1.4852	nitrogen 1156ppm	nitrogen 586ppm	52 / 15	Degassing/
5	80	Heat resistant	nitrogen: 815ppm	nitrogen: 394ppm	96	Decarburization
6	80	Hastelloy C22	carbon 0.466%	carbon 0.395%	71	Decarburization
7	80	Nickel based	carbon 0.071%	carbon 0.003%	74	Decarburization

In case study number 1 described above, done with 1.3243 tool steel, were carried out some industrial trials using the VCAP furnace to compare air-melted parts vs. VCAP melted castings. The intention was to obtain a better understanding of gas-related casting defects such as pinholes, nitrides, oxides, and gas porosity. To a certain degree, gas levels can be controlled in air melting using deoxidation agents such as aluminium. However, this can cause different issues like non-metallic inclusions. Consequently, a vacuum treatment can be applied but can add significant costs to the entire process. Therefore, a vacuum treatment was tried and validated against a traditional air melt process. For trial purposes, a 1.3243 tool steel was chosen due to its sensitivity for gas solubility. [3]

Fig.5 - Tapping stage of trial heat with 1.3243 tool steel at Brno University of Technology.[3]

These are the gas level evolution during trials based on different samples taken:

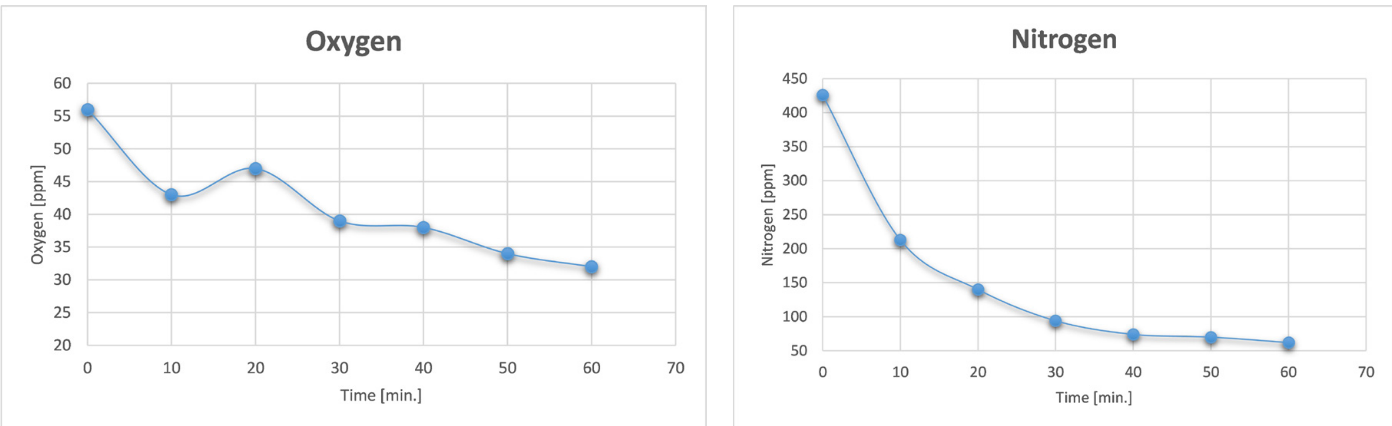


Fig.6 - Oxygen/nitrogen evolution during the VCAP trial melt.[3]

The following picture shows an example of the internal casting defect:

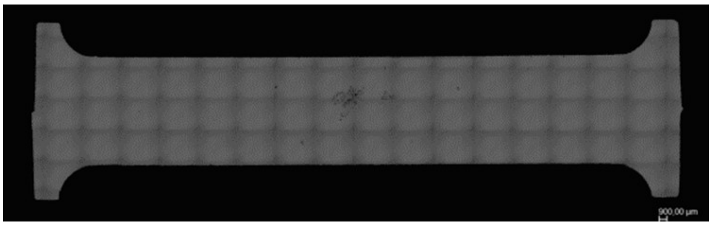


Fig.7 - Example of an inner casting defect shown in an X-Ray picture.[3]

As a conclusion from the tests done, it was noticed that the VCAP melt shows a significantly lower gas level compared to an air melted alloy. Additionally, no significant loss of alloying elements was observed during VCAP melting. The microstructure is currently being examined and shows promising first results; however, no data can be published yet. [3]

Case studies from production sites

The following cases studies summarize the tests done at production sites:

Tab.2 - Summary of VCAP tests done in production sites.

N.	Size (kg)	Alloy	Initial value	Final value	% of reduc.	Comments
1	800	Super Duplex 2507 Stainless Steel	carbon 0.060%	carbon 0.029%	52	Decarburization
2	2,500	IN625 Ni alloy	carbon 0.043%	carbon 0.029%	33	Decarburization
3	2,500	Hast C22 Ni alloy	carbon 0.045%	carbon 0.018%	60	Decarburization
4	2,500	AISI 316 Stainless Steel	carbon 0.030%	carbon 0.015%	50	Decarburization
5	1,100	Carbon Steel	O2/N2/H2: 116/265/6.3 ppm	O2/N2/H2:	47/58/54	Degassing
6	800	CF8M Austenitic steel	O2/N2:	62/111/2.9 ppm	78/34	Degassing
7	800	CF8M Austenitic steel	322/848 ppm	O2/N2:	77/37	Degassing

The following picture shows a real tapping stage from a VCAP furnace in a production site:

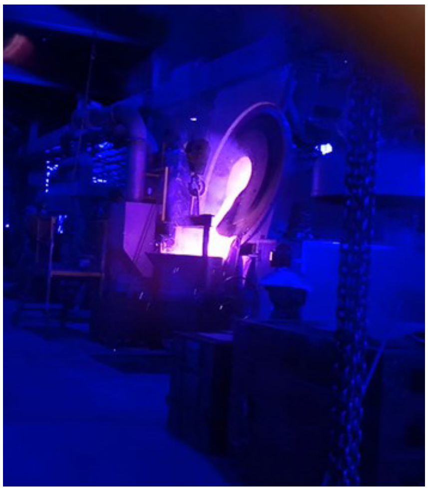


Fig.8 - 2.5t VCAP tapping stage on IN625 alloy.

FINAL CONCLUSIONS

VCAP technology is a hybrid technology between existing air melting and vacuum melting technologies.
It combines the simplicity of air melting process and benefits from vacuum melting, such as reduction of deleterious gases like Hydrogen, Oxygen (by deoxidation) and Nitrogen, low vapour pressure tramp elements like Pb, Cd, Bi, Zn.
Moreover, VCAP process can also perform decarburization and desulphurisation reactions to reduce Carbon and Sulphur respectively.

As a result of the benefits of VCAP technology, foundries can achieve process improvements and significantly reduce scatter in product properties and characteristics, so a more consistent casting process and less rejections on cast parts. This is because VCAP enables better chemical control of the alloys casted, better micro-cleanliness, clear improvement of mechanical and foundry properties, and an improvement of technological characteristics, like hot workability, weldability and machinability.

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