VACUUM MELTING, REMELTING and CASTING - a must for highest end materials

This paper deals with several topics of melting, remelting and casting under vacuum. In the first part it will be shown how the application of vacuum leads to an improvement in metal cleanliness in specialty steels and superalloys and in part two we present an overview of modern melting, remelting and casting equipment.

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In recent years the world of metallurgy has seen a massive growth in installations of new melting, remelting and casting equipment under vacuum. This development is driven by various factors, but mainly by the increasing demand from aerospace and power turbine industries, which pursue the simple philosophy "Impurities which are not generated – do not have to be removed". This means, especially for materials which are used in rotating parts under high thermal stress, that cleanliness is very important and influences the lifetime of such parts. For example Low Cycle Fatigue (LCF) properties of turbine disks can be directly related to both non-metallic inclusion content and inclusion size of the material.

In aircraft and land based gas turbines most of parts and components (e.g. Turbine Blades and Vanes, Turbine Disks, Cases, Shafts, Bolts, Combustors), which undergo a high thermal stress during operation, are made of superalloys. Table 1 gives examples of type and composition for such superalloys. It is evident from Table 1 that most of these superalloys are nickel based alloys with different amounts of other alloying elements.

Alloy	Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	Other
IN-100	10	60	15	3	---	---	4.7	5.5	<0,6	0.15	0,06 Zr, 1.0 V
Inconel 718	19	52.5	---	3	---	5.1	0.9	0.5	18.5	0,08 max	0,15 max Cu
Rene 88	16	56.4	13	4	4	0.7	3.7	2.1	---	0.03	0,03 Zr
Udimet 720	18	55	14.8	3	1.25	---	5	2.5	---	0.035	0,03 Zr
Waspalloy	19.5	57	13.5	4.3	---	---	3	1.4	2,0 max	0.07	0,006 B, 0,09 Zr
Inconel 625	21.5	61	---	9	---	3.6	0.2	0.2	2.5	0.05	
Hastelloy C-276	15.5	59	---	16	3.7	---	---	---	5	0,02 max	

Tab.1 Typical superalloys used in aeroengines

In Figure 1 a general overview about alloying elements in superalloys is shown. Most of these alloying elements have a high affinity to oxygen, nitrogen and hydrogen. Therefore, during melting of such alloys under air, formation of oxides and/or nitrides will occur. As mentioned before, these oxides and nitrides have a dramatic influence on mechanical properties of the materials. To minimise or avoid the formation of inclusions, it is therefore necessary to protect the melt from contact with air.

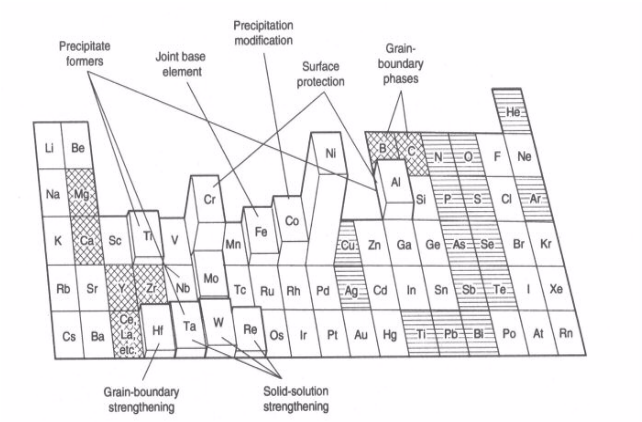

Fig. 1 Alloying elements used in nickel-base superalloys. [1]

Vacuum Metallurgy - Fundamentals

According to Sievert's law, the amount of dissolved gaseous elements in a melt strictly depends on the partial pressure of these gases in contact with the melt. For example the nitrogen dissolution is described by the following reaction equation:

$$\frac{1}{2}(N_2) \leftrightarrow [N]$$

Here nitrogen in parentheses means gaseous N_2 and nitrogen in brackets means dissolved nitrogen, respectively. This takes into account, that diatomic gases are dissolved in monatomic state.

In case of multi-component systems the nitrogen content is also determined by equilibrium reactions of alloying elements with nitrogen. For example, a four component alloy which contains iron, nickel, chromium and titanium. In this system titanium has by far the highest reactivity with nitrogen. Hence, nitrogen will react with titanium to form titanium nitrides. This reaction will proceed until an equilibrium value has been reached.

To avoid such a formation of nitrides it is necessary to reduce the nitrogen content before alloying with reactive elements. In this way it is possible to reduce formation of non-metallic inclusions also during solidification.

Another reason for application of vacuum melting is the removal of trace elements by evaporation. The evaporation rate of an element from a melt can be described by the Langmuir-Hertz-Knudsen equation under conditions of free evaporation. Vacuum favours evaporation, because there is no gaseous phase above the melt which can interact with vapours coming out of the melt

High alloyed steels or superalloys require very low carbon contents to prevent formation of carbides and to improve weldability. Another main reason for the application of vacuum melting is the pressure dependence of the CO-reaction: Only under reduced partial pressure of carbon-monoxide, decarburisation without massive losses of reactive alloying elements (e.g. Cr, Ti) can be achieved.

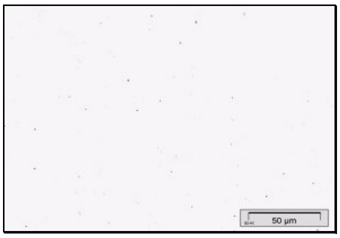

Fig. 2a SUS 316L produced in a VIM

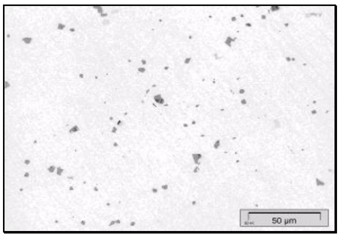

Fig. 2b SUS 316L produced in EAF-AOD

Comparison of Figures 2a and 2b gives a rough idea of how much melting under vacuum can improve the cleanliness of a stainless steel. While the melt shown in Fig. 2a was totally made in a **V**acuum **I**nduction **M**elting Furnace (VIM) from virgin raw materials, the melt shown in Fig. 2b was produced in a conventional process route (EAF – AOD – Continuos Casting). Inclusions in Fig. 2a are of oxide-type and inclusions in Fig. 2b are oxides surrounded by nitrides. Even though it is quite difficult to avoid the formation of very small oxide inclusions (< 1 µm) in vacuum melting, at least the formation of bigger non-metallic inclusions can be avoided.

The main advantages of melt treatment under vacuum can be summarised as follows:

- **Extensive degassing of melts (e.g. hydrogen < 1 ppm)**
- **Significant reduction of non-metallic inclusions (oxides, nitrides) compared to melting under air**
- **Deoxidation by carbon (down to low levels of oxygen) without formation of solid or liquid reaction products**
- **Ability to manufacture very low carbon high strength steels or superalloys**
- **Evaporation of trace elements**

All above listed advantages of melting under vacuum are important for both superalloys and specialty steels. Especially during the last ten years more and more high quality steels have been produced in vacuum melting and remelting facilities. Particularly, remelting technology has become important in terms of further inclusion removal and microstructure control for forgings.

Vacuum Melting, Remelting and Casting

The following overview shows many different processing routes for high end materials, according to their requirements.

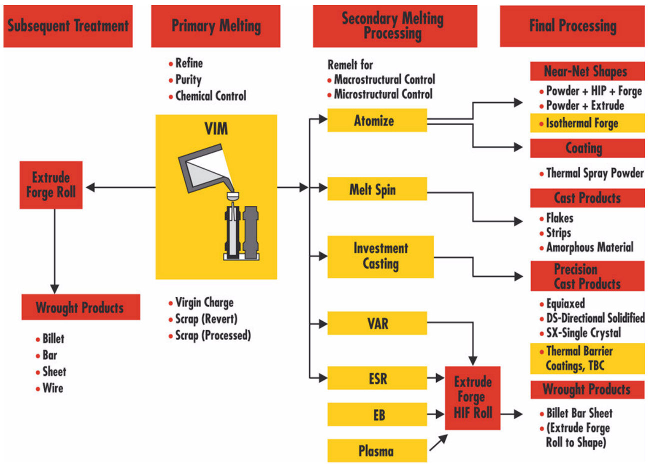

Fig. 3 Processing routes for superalloys and high quality steels

VIM/VIDP

The VIM or VIDP is the central core of every vacuum refining operation. Here melting, refining and alloying are done under controlled conditions. With melting capacities from a few kilograms up to 30 tons VIM/VIDP-furnaces offer a wide range. While in smaller sized furnaces (5 - 500 kg) VIM is the preferred melting tool, for larger charge weights (above 2 tons) **V**acuum **I**nduction Melting **D**egassing and **P**ouring (VIDP) is the most suitable furnace type. In this unique vacuum melting system the crucible itself acts as the vacuum melt chamber (Fig. 4). VIDP-furnaces provide faster pump down compared with chamber-type VIM's of the same melting capacity, because of the dramatically reduced chamber volume.

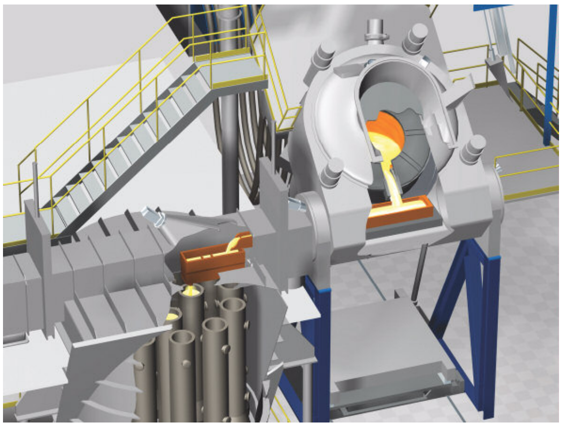

Fig. 4 VIDP-furnace pouring a melt

Operating pressures of 10^{-3} to 10^{-2} mbar, leakage rates down to $5x10^{-3}$ mbarl/sec and melt bath movement by specially designed stirring coils ensure high process reliability and uniform product quality under a wide field of operating conditions. Furthermore, the VIDP multi-chamber concept allows to keep the crucible all the time under vacuum. The melt is transferred via launder into the mould chamber, where either electrodes for subsequent remelting processes or bar sticks for investment casting are produced.

ESR/IESR/PESR/VAR

Electro **S**lag **R**emelting with its variations **I**nertgas **E**lectro **S**lag **R**emelting and **P**ressure **E**lectro **S**lag **R**emelting are common remelting processes. Here an electrode is melted down by heating a synthetic slag. Due to the superheated slag that is continuously in touch with the electrode tip, a liquid film of molten metal forms at the electrode tip. As the developing droplets pass through the slag, the metal is cleaned of non-metallic inclusions which are removed by chemical reaction with the slag or by flotation to the top of the molten pool. The remaining inclusions are very small in size and evenly distributed in the remelted ingot. Besides this refining feature, the ESR process allows to establish a defined macrostructure, due to the controlled solidification in a water-cooled copper mould. Thus segregation is minimised and a uniform distribution of alloying elements can be achieved. This is quite important, especially for high alloyed materials (maraging steels, tool steels, superalloys).

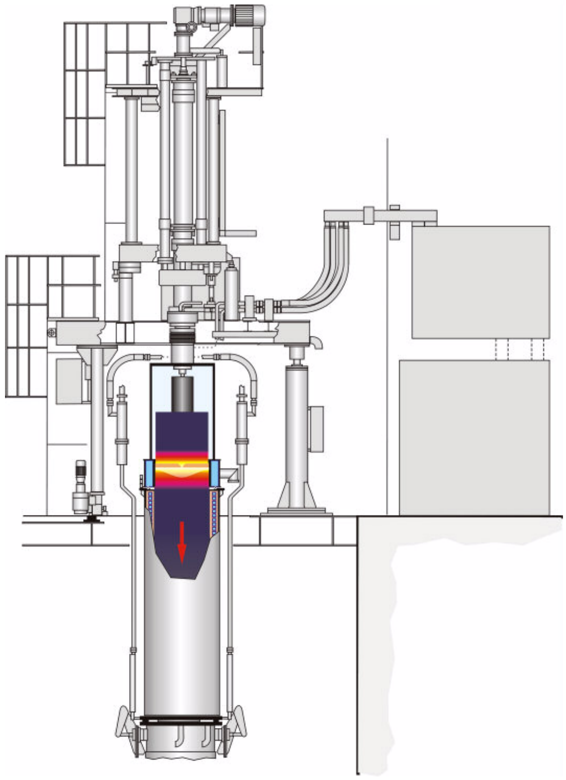

Fig. 5 IESR-furnace

In Figure 6 a comparison of cleanliness values from different steelmaking processes is shown. With ESR better cleanliness values as compared to open air melting in an EAF are achieved, whereas with PESR and **V**acuum **A**rc **R**emelting (VAR) a further improvement, also in terms of narrower scatter of the values, is obvious. Especially IESR, PESR and VAR with their controlled furnace atmospheres or vacuum are the most suitable tools for proper adjustment of material properties.

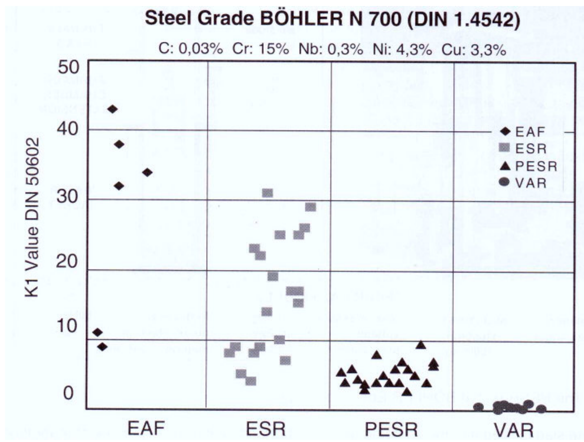

Fig. 6 Typical cleanliness values [2]

The so called triple melting process which comprises VIDP/IESR/VAR is specified for some forged parts for the aerospace industry and offers the optimum in materials refining.

VIM-IC (**V**acuum **I**nduction **M**elting and **I**nvestment **C**asting)

The majority of vacuum investment castings such as turbine blades and vanes for the aircraft and industrial gas turbine industries are made from Ni-base superalloys and are produced in VIM-IC furnaces. In these furnaces, a master alloy barstick is inductively melted and then cast into an investment mould. The solidification structure of the casting can be adjusted to be equiaxed (E) or, through the use of an additional mold heater, directionally solidified (DS) or single crystal (SC).

DS/SC solidified components have increased strength at high temperatures close to the melting temperature of the alloys.

For the production of large directionally solidified (DS) and single crystal (SC) components high thermal gradients are required. In order to provide the best solidification conditions with highest thermal gradients, the **L**iquid **M**etal **C**ooling (LMC) process is utilized. In the LMC process, the filled mould is immersed into a cooling bath, either consisting of liquid aluminum or liquid tin.

Fig 7 VIM-IC furnace

Depending on the required solidification structure and the size of the cast components, vertical VIM-IC furnace designs up to approx. 200 kg or horizontal VIM-IC furnace designs for larger cast weights are utilized.

EB/PVD (**E**lectron **B**eam/**P**hysical **V**apor **D**eposition) Coating of Turbine Blades and Vanes

Increasingly stringent demands are being imposed on the efficiency of gas turbine engines employed in aerospace and power generation industries. This is driven by the requirement to reduce consumption of fossil fuels and thus operating cost. The major means for improving turbine efficiency is by increasing operating temperatures in the turbine section of the engines. The materials employed must withstand the higher temperatures as well as mechanical stress, corrosion, erosion and other severe conditions during operation, while providing extended lifetime as required by the end users. This is an area where EB/PVD coating processes make a significant contribution today.

The paper-thick coating allows gas temperatures, which can be 100 to 150 °C higher than the melting temperature of the nickel base alloy. Yttria-stabilized ZrO_2 has been proven to be the ideal material for these coatings.

The major factor determining quality of the coated layer is the process that takes place in the coating chamber. A homogeneous cloud of vapor must be generated. In order to accomplish this, the coating material must be dosed in the right quantity, sufficient reactive gas must be added, the right scanning pattern of the electron beam over the molten material selected and last but not least the blades must be moved inside the vapor cloud in a pre-assigned motion.

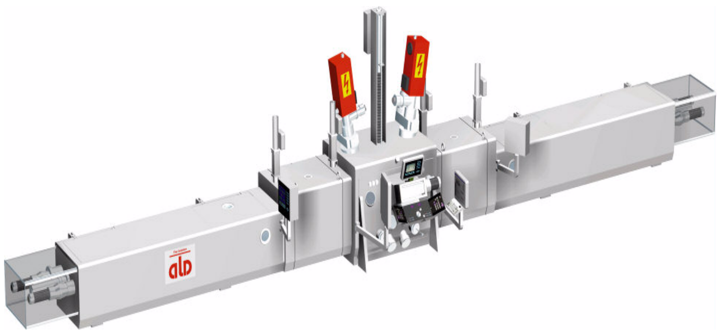

Fig 8 Typical EB/PVD coating system for production of Thermal Barrier Coatings (TBC)

VIGA (**V**acuum **I**nert **G**as **A**tomisation)

For some superalloy or steel grades it is nearly impossible or not feasible to produce large ingots by melting and remelting technology. Because of their high alloy content of refractory metals such as Nb, Ta, Mo, W e.g., high speed steels and IN 718 are limited to maximum ingot diameters of 400-500 mm. Above these diameters segregation will occur and/or size, shape and distribution of carbides are unacceptable. The most suitable way to overcome these problems is offered by the powder/ HIP route. Here in the first step metal powder is produced and in the second step this powder is compacted by the **H**ot **I**sothermal **P**ressing-process (HIP) to large ingots or pre-forms.

Powder production is done by inert gas atomisation, where a liquid metal is disintegrated by the kinetic energy of a high pressure inert gas stream. The metal droplets solidify in flight in the atomization tower located directly underneath the atomization nozzle. The powder/gas mixture is transported via a conveying tube to the cyclone where the powder fractions are separated from the atomization gas. The metal powder is collected in sealed containers which are located directly below the cyclones. Afterwards the powder is separated in several fractions and encapsulated. While in former times only superalloy powders and reactive metal powders were produced by vacuum melting and inert gas atomisation, recently also the producers of tool steel powders intend to refine the melt in a vacuum system before atomization. The main reason for this development is the outstanding cleanliness of vacuum melted material, which also improves the powder quality.

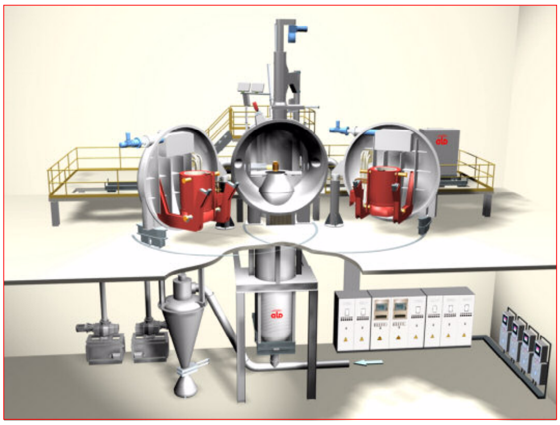

Fig. 9 2 x 2 t batch weight VIGA-system

Up to now VIGA-systems with a capacity of 20 kg – 2 t batch size have been realised.

Conclusions

Vacuum melting, remelting and casting technology becomes more and more a requirement for materials which are used in high end applications. The cleanliness of speciality steels or superalloys produced by vacuum melting is much better than that attained by conventional processing methods. Last but not least, vacuum melting and remelting technology gives steel companies the opportunity to add value to their products and to supply more speciality-grade steels and alloys to their customers.

References

[1] M.J. Donachie and S.J. Donachie, "Superalloys: – a technical guide", 2nd ed., 2002, ASM International

[2] R. Schneider et al, "Pressure-Electro-Slag-Remelting (PESR) for the production of nitrogen alloyed steels", Proc. 5th Int. Conf. on Tooling, Leoben, Austria, 1999, p. 265