Vacuum Melting

Technological developments during World War II demonstrated the feasibility for products such as gas turbine engines and nuclear reactors; after the war commercial and military use of these products created a large demand. The combination of high temperature, stress, and oxidative operational environments for these products was much more severe than what was required for other products in the past. Designers and metallurgists used refractory metals (alloys of Ti, Nb, Mo, and W) and nickel base superalloys to function in these hostile environments. In the liquid state these materials are very reactive with oxygen, nitrogen, carbon, and in many cases hydrogen. During solidification, the reaction products precipitate as ceramic and/or intermetallic particles which act as nucleation sites for fatigue cracks. Early work showed that melting these materials in a vacuum or controlled atmosphere produced the improved fracture toughness and resistance to fatigue that is required in the operational environment. The equilibrium thermodynamics of these vacuum melting systems is depicted schematically in a Ellingham diagram (Richardson 1974, vol. 2). Up until the late 1940s vacuum melting processes which included vacuum induction melting (VIM), vacuum arc remelting (VAR), and electron beam melting (EBM) were laboratory scale units used to produce small research quantities of materials. During the 1950s and 1960s the commercial demand for these vacuum-melted materials increased from 10^5 kg to over $2\times10^8\,\mathrm{kg\,yr^{-1}}$ (Nisbet 1967). This tremendous growth rate fueled innovations in furnace design, operation, and process control to create the mature vacuum melting industry of today. Vacuum-melt processing is critical to the existence of many of the advanced alloy systems that are used today in the aerospace, industrial, and energy industries. Vacuum melting is what makes possible the design and use of alloys with elements that are highly reactive when molten and exposed to the atmosphere.

1. Vacuum Induction Melting

Vacuum induction melting is used to melt and cast superalloys and high-strength steels which require vacuum processing because they contain refractory and reactive elements such as Nb, Ti, Al, etc. Furnaces used in casting operations are primarily "melt and pour" in a vacuum or controlled atmosphere. In this case the charge material chemistry is the same chemistry as that desired for the casting. Casting furnace pour weights range from 1 kg up to 500 kg with the majority of units rated in the 50 kg range. Furnaces used in alloy production are designed with capabilities to manipulate the thermodynamics and chemistry so that desirable elements are retained in the liquid metal at the level required by the recipe and undesirable elements (e.g., O_2, N_2) are removed from the liquid metal. Nitrogen is removed by bulk evaporation and oxygen is removed by carbon in a carbon boil creating CO gas with both gases being removed through the vacuum pumps. Thus, both carbon and oxygen are manipulated in a dependent fashion. The primary strategy during VIM is to get the bath in a "clean state" before the reactive metal additions are made. Many melters also cover the bath with a CaO slag to reduce sulfur.

Pour weights for furnaces used to produce alloy range from 25 kg to 27 000 kg with the majority of units rated at ~7000 kg. The first known large commercial furnaces (3600 kg) were installed in Germany in 1923. The vacuum system was only capable of achieving a furnace pressure of ~800 Pa, whereas most modern vacuum induction furnaces are capable of achieving ultimate pressures less than 1 Pa. A 10 kg unit, the first commercially installed unit for casting turbine blades at Special Metals Corp., New Hartford, NY in 1952, is now designated an ASM historical landmark. All VIM furnaces utilize a ceramic crucible to contain the metal, and heating is accomplished by suscepting an a.c. magnetic field generated by a water-cooled coil which surrounds the crucible. The susceptor can either be a hollow graphite cylinder surrounding the melting crucible or the metal charge. In both systems the magnetic field generates eddy currents within the susceptor which create internal resistance heating. The depth of penetration of the eddy currents is inversely proportional to the frequency in the coil. Greater stirring of the molten metal is achieved at larger penetration depths. Thus, the frequency of the power supply must be tuned to the furnace geometry. In addition, the coil must also be carefully insulated to prevent voltage breakdown between coil turns in the vacuum ambient. The types of metal alloys that can be melted in VIM are determined by compatibility of melt and ceramic. Crucibles for superalloys are usually made from mixtures of MgO–Al_2O_3. Pour systems such as launders and tundishes are sometimes used to transfer the alloy from the crucible to the molds. Also ceramic foam filters are sometimes incorporated into the transfer system to reduce turbulance and to remove oxide particles. Filters have become particularly important in investment casting systems (Mancuso *et al.* 1988). Refractory (oxide) crucibles are prone to react with the molten metal. For instance, molten aluminum can reduce the MgO in the crucible lining to form aluminum oxide and magnesium. Crucible reactions are slowed down once a reaction layer is formed at the molten metal/crucible interface (Sutton and Maurer 1979).

The product from alloy production furnaces are usually long cylindrical ingots cast in iron or steel molds. These ingots range in diameter from 0.1 m to 1 m. Since ingots are usually very long (>2 m) compared to the diameter, solidification is almost horizontal from the mold wall into the center. This condition results in entrapped solidification shrinkage or pipe cavity, and for this reason these ingots are primarily used as electrodes for subsequent VAR or electroslag remelting (ESR). A photograph of a 1.4×10^4 kg capacity alloy production furnace is shown in Fig. 1. The primary advantage of VIM is the capability of producing a precision chemistry in a vacuum environment and excellent mixing and the shortfalls include the fact that the melting and processing take place in a ceramic crucible and the difficulty in feeding solidification shrinkage.

A variant of VIM called induction skull melting (ISM) is finding increasing use in Ti and Zr casting furnaces. At present the maximum capacity of these furnaces is ~ 50 kg of Ti. The crucible is composed of many vertical water-cooled Cu segments, each separated by a thin slots (Rishel *et al.* 1999). This arrangement minimizes induced currents in the Cu segments, thus allowing the induction field to pass through the segments and couple to the metal charge. As the name implies a thin skull of the metal being melted forms on the crucible wall and so the melt is contained in metal of the same chemistry. The same skull can be used for many melts as long as the melt chemistry remains the same. A schematic of the ISM crucible is shown in Fig. 2. Advantages of this process include intense induction stirring, the ability to melt scrap and revert, melt in a vacuum or controlled atmosphere, and the absence of ceramics. Disadvantages include the requirement of a much larger power supply than VIM, low melt weight, a limited melt superheat, and skull removal every time the melt chemistry is changed.

2. *Electron Beam Melting*

Up to the 1960s electron beam melting was primarily used to consolidate Ta, Nb, Mo, and W by drip melting into water-cooled Cu crucibles. In some instances the resulting ingots were subsequently vacuum arc remelted. These materials were electron beam melted because they are embrittled by O, N, and in some cases H, they have very high melting points, and there are no ceramics present in the electron beam furnace. Refractory metals were the first candidates for EBM, because the furnace chamber operating pressures were quite low, ~ 0.133 Pa, and the ambient furnace conditions could be tolerated by the available electron gun technology. Electron guns must operate at voltage, power, and pressure levels below the conditions for high voltage breakdown or arc down.

From a practical standpoint this means that the pressure in the emitting region of the gun must be as low as possible (10^{-2}–10^{-3} Pa) and decoupled from the ambient conditions in the melt chamber. Arc downs lower productivity because of shortened cathode life, furnace down time, and interrupted solidification. During the 1960s new gun and power supply designs were developed which enabled the gun to tolerate higher-pressure ambient conditions (~ 6.7 Pa) that are common during melting of Ni and Ti alloys while in many instances operating at power levels greater than 10^3 kW. Major innovations included rapid gun shutdown and automatic restart, pumping of the gun chamber with separate vacuum pumps, and blocking of ambient gas diffusion from the melt chamber into the gun cavity by

Figure 1
Cutaway of a production 1.4×10^4 kg VIM furnace (reproduced by permission of ALD Vacuum Technologies).

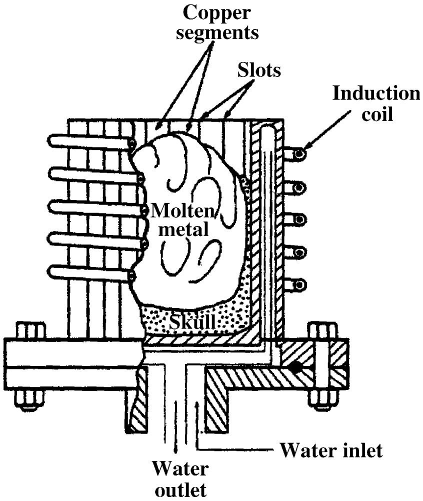

Figure 2
Schematic of an induction skull melting crucible and molten charge (Chronister *et al.* 1986).

bleeding gas into the focusing region of the gun. Electron beams can be easily guided with a magnetic lens system located at the bottom of the gun. More details involving electron gun design and operation can be found in Schiller *et al.* (1982).

Building on these innovations, furnaces to process Ti alloys were designed for continuous introduction of scrap, sponge, and turnings. The molten metal is processed in long, shallow water-cooled copper hearths before casting into round or slab molds by a process similar to continuous casting (Entrekin and Harker 1984). A skull forms on the surface of the water-cooled hearth and becomes the container for the molten metal. An example of such a furnace is illustrated in Fig. 3. Advantages of this processing include the removal of high-density inclusions of WC, originating from machining tools, by sinking to the bottom of the hearth, decomposition and/or capture of hard α-particles (TiN) because of the long dwell time in the liquid, and the ability to recycle Ti scrap. At the present time rotor-grade certification requires that electron beam melted ingots be subsequently vacuum arc remelted before the material can be used in rotating parts.

One of the biggest, yet unexploited, advantages of electron beam melting is the potential to precisely control solidification. Since the electron beam can be accurately focused and deflected much faster than the thermal diffusion speed in the ingot, it should be possible to control, in space and time, the thermal environment in the solidification region. Online coupling of this control capability with numerical simulation could provide the potential to use EBM as the final melt process and the potential to process superalloys that are subject to severe macrosegration. Disadvantages of EBM include evaporation of high vapor pressure elements, high capital cost, difficulty in controlling melt rate, the fact that the skull must be changed when melt chemistry is changed, and limitation in melt chamber pressure.

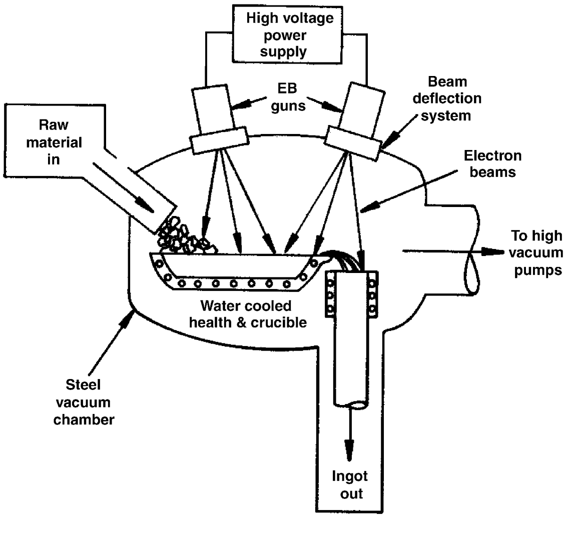

Figure 3
Schematic representation of the electron beam cold hearth refining process (courtesy of Timet Corp.).

3. Vacuum Arc Remelting

Vacuum arc remelting is a widely applied vacuum melting process used to control the solidification of segregation sensitive alloys. It is most commonly the final liquid metal processing step before forging. The first furnace, resembling furnaces in operation today, was built by vonBolten in 1903 (Noesen 1967). Ingots produced by air melting, ESR, VIM, and EBM are utilized as electrodes in the VAR process. Materials melted by VAR include high-strength steels, Ni base alloys, Ti base alloys, refractory metals, and U alloys. Premium quality material, called triple melt, processed by VIM/ESR/VAR, is used to produce rotating disks for gas turbine engines. Ingots produced by VAR range in size from 0.05 m to 1 m in diameter and weigh from 1 kg to 1.8×10^4 kg. VAR is carried out in furnaces similar to the illustration in Fig. 4. In this unit the electrode is suspended from a water-cooled Cu ram into a long cylindrical water-cooled Cu crucible. The entire assembly containing the electrode and crucible is evacuated and the electrode and crucible are connected to the negative and positive bus bars, respectively, of a large d.c. power supply. Melting commences after a metal vapor arc is started between the electrode and crucible bottom. Molten metal

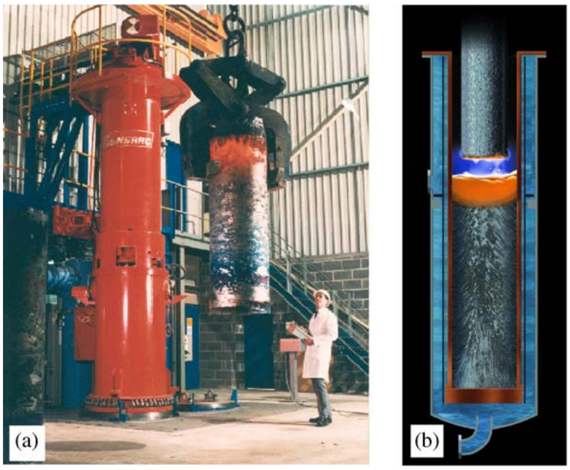

Figure 4
Photograph (a) and cutaway (b) of a production VAR furnace (courtesy of Consarc Corp.).

drips from the electrode into a molten pool contained by the crucible, and at steady state, the average solidification rate is equal to the melt rate. Melting currents range from 0.5 kA to 35 kA, voltages from 18 V to 40 V, and melting rates from 12 g s^{-1} to 250 g s^{-1}. Solidification starts at the crucible wall and proceeds inward with upward curvature so that the columnar dendrites are almost vertical at the ingot centerline. When the thermal gradient in the center region is low (caused by a high melt rate creating a deep pool), equiaxed grains will be found in the center region of the ingot. There is a general consensus in the industry that ingots with complete columnar structure yield the highest-quality material. Since molten metal is added to the pool atop the ingot as solidification is proceeding upward, the solidification shrinkage is constantly being fed resulting in a solid ingot.

The arc is the heart of the VAR process. It provides the electrical conduction path which couples the electrode and molten pool, and provides the heat for melting. The arc is sustained by ionized metal vapors evolved by evaporation from the electrode (cathode) and molten pool (anode). Ingot quality is controlled by how uniformly the arc injects current into the molten pool. Control variables melt rate and electrode gap are manipulated to control the arc and provide a steady heat source. Arc behavior is optimized when the arc behaves as a macro-uniform heat source as viewed from within the solidifying region. This optimized arc behavior is coined a diffuse arc. Under some furnace environments, the arc plasma can become constricted and the conditions of macro-uniform heating no longer apply.

From breaker physics work on "vacuum or metal vapor arcs," it is known that this type of arc simultaneously consists of many plasma columns anchored by cathode spots which in effect are electrical parallel circuits (Zanner 1979). The number of columns at any instant is a function of the thermal properties of the cathode. For example, for materials composed of iron or nickel each cathode spot is allocated ~50 A and ~300 A for tungsten. Thus, for a 5 kA Ni or Fe arc one could expect ~100 cathode spots burning simultaneously, or ~100 parallel circuits wherein current is transferred from the cathode to the anode. The cathode spots are highly mobile and travel radially at velocities of ~10 m s^{-1} from the central region of the cathode to the outside edge and up the side wall of the electrode before they are extinguished. The cathode spots in multiple cathode spot arcs appear to have a random motion because of the interaction of magnetic fields between spots. Since the spots move much faster than the thermal diffusion speed in the electrode materials, the arc appears to the electrode face and molten pool as a macro-uniform heat source. Metal transfer (in the form of drips which create shorted columns) from the cathode to the anode must also be considered regarding the uniformity of the arc heat source in a VAR furnace. During the short, current can increase to very high levels depending on the inductance of the system and the lifetime of the short. Normal shorts have lifetimes of from 0.1 ms to 5 ms and frequencies of ~5–20 Hz. It is speculated that these events are damped on the timescales of the fluid motion in the pool, ~5–10 cm s^{-1}. The frequency of drip short formation is inversely proportional to electrode gap length and this relationship is used to dynamically control the gap. Under optimal conditions of a diffuse arc the current is uniformly distributed across the electrode faces creating a constant melt rate and steady flows in the molten pool atop the ingot. The light emitted from the electrode and crucible (annulus region) appears to be of constant flickering (flickering is due to the drip shorts) intensity with the plasma background appearing about the same as the sky on a sunny, but hazy day, as viewed from a monitor in the control room. When the arc is in the diffuse mode, there is no plasma rotation or momentary bright areas in the annulus. Voltage, current, melt rate, and pressure traces appear to be steady over time periods of hours. The background furnace pressure can be less than 1 μm, but the pressure inside the plasma column is speculated to be much higher. Diffuse arcs are stabilized by arc gaps less than 12 mm, low furnace pressure, and a clean molten pool surface (no slag). Diffuse arcs provide optimum material quality and it is very important to maintain a diffuse arc during melting.

A constricted arc is just what the name implies, a constricted plasma column. Constricted arc mode is the most dangerous with respect to ingot quality. When the arc is burning in this mode, current is injected into the molten pool in concentrated fashion by the constricted plasma column. The plasma column usually rotates in a clockwise fashion taking tens of seconds to make a revolution as observed from the control room monitor. The nonuniform current injection disturbs the steady fluid flows within the molten pool and allows the creation of shelf at the ingot/crucible boundary. The easiest way to detect a constriction is by visual appearance on the control room monitor. The light emitted from the annulus region will appear to periodically change intensity going from bright to dark. When the annulus region appears dark, one can sometimes observe a shelf growing in from the crucible wall which will disappear when the region appears bright (the constriction melts away the shelf). In less severe forms of constriction, the arc can exist simultaneously in a diffuse/constricted mode with a portion of the total melting current allocated to the constricted column. At the same time pressure spikes will sometimes be present and the voltage may periodically decrease by 0.5–1.5 V. A constricted arc can cause large variability in the drop short rate and a depression in the melt rate if it occurs over periods of tens of minutes. The primary causes for a constricted arc are slag on the pool surface, the presence of a molecular gas such as CO or N_2, or the evolution of volatile elements from a poorly conditioned electrode surface. The propensity to create an ingot defect with a constricted arc varies with ingot size, the periodicity of the constriction (time on versus time off), the magnitude of current allocated to the column, and whether melt back occurs within the pool. Conditions commonly labeled as "glows" are usually severe arc constrictions. Channel segregates (freckles) and dirty white spots can be caused by constricted arcs. At the present time the melting community is undertaking a large research effort to develop multiple variable control systems based on numerical simulation to control pool shapes and arc behavior.

Advantages of the VAR process include a ceramic free system, control of solidification shrinkage, ability to consistently produce optimal solidification structures in superalloy ingots as large as 1 m in diameter, and melting in a vacuum environment. Disadvantages include the sensitivity of solidification structure to arc behavior and the potential for a hydrogen explosion if a water leak develops while melting Ti.

A variant of the VAR process called skull melting is widely used for casting Ti and other reactive metals. In this case the water-cooled Cu crucible has a tilt capability for pouring castings. The electrode is melted at a very high rate, and after the crucible is filled with metal it is immediately tilted to pour the metal into a mold. Advantages of this process include the absence of ceramics, the ability to melt large amounts of metal ($\sim$1000 kg Ti), and melting in a vacuum ambient. Disadvantages include very low superheat and the need for a fabricated electrode, a large power supply (some units require 80 kA), and the danger of a hydrogen explosion while melting Ti.

4. Summary

Selection of the vacuum melting process used to produce an alloy is based on the reactivity of the alloy, the melting temperature, the size of the ingot required to make the hardware, the cost of the production operation, and the quality requirements needed for the hardware to perform in the operating environment. Vacuum melting and solidification requires tightly controlled processes to produce consistent macrostructures. For example, as mentioned above triple melt is the default process scheme to produce superalloy ingots for gas turbine rotating hardware. In the triple melt process VIM is used to produce the alloy chemistry and microcleanliness, ESR is used to produce a low sulfur consolidated electrode, and VAR is used to produce the desired solidification structure. New technology can have a dramatic effect on process substitution. Improvements in control schemes for EBM could make it possible to meet the triple melt requirements with a single electron beam melt. There is a constant struggle to reduce cost and improve quality, and this produces evolutionary improvements which ripple through the entire process stream from start to finished product creating, for example, a positive effect on the energy and transportation sectors of the world economy.

Bibliography

Bertram L A, Zanner F J 1981 Interaction between computational modeling and experiments for vacuum arc remelting. In: Brody H D, Apelian D (eds.) *Proc. Modeling of Welding and Casting Processes*. AIME, Warrendale, PA, pp. 333–49

Bunshah R F 1962 *The History of Electron Beam Technology*. Wiley, NY

Chronister D J, Scott S W, Stickle D R, Eylon D, Froes F H 1986 Vacuum melting *JOM* **9**, 51–4

Entrekin C H, Harker H R 1984 Electron beam cast titanium slab. In: Bhat G K, Lherbier L W (eds.) *Proc. Vacuum Metallurgy Conf.* AVS, NY, pp. 45–8

Mancuso S O, Sczerzenie F E, Maurer G E 1988 The investigation of minor element additions on oxide filtering and cleanliness of a nickel based superalloy In: Duhl D N, Maurer G, Antolovich S, Lund C, Reichman S (eds.) *Proc. Superalloys* 1988. AIME, Warrendale, PA, pp. 377–86

Nisbet J D 1967 Progress of vacuum metallurgy in North America. In: Foster E (ed.) *Trans. Int. Vacuum Metall. Conf.* AVS, NY, p. 17

Noesen S J 1967 Vacuum arc melting from Robert Hare—1839 to the present. In: Foster E (ed.) *Trans. Int. Vacuum Metall. Conf.* AVS, NY, pp. 503–50

Richardson F D 1974 *Physical Chemistry of Melts in Metallurgy*. Academic Press, NY, Vols. 1–2.

Rishel L L, Pollock T M, Cramb A W 1999 Induction skull melting of titanium aluminides. In: Mitchell A, Ridgeway L, Baldwin M (eds.) *Proc. 1999 Int. Symp. on Liquid Metal Processing and Casting*. Santa Fe, NM, pp. 287–99

Schiller S, Heisig U, Panzer S 1982 *Electron Beam Technology*. Wiley, NY

Schlatter R 1972 Melting and refining technology of high-temperature steels and superalloys. In: *Proc. 2nd Superalloy Conference*. AIME, MCIC-72-10, pp. A1–40

Smith H R 1967 Electron beam processing in vacuum metallurgy. In: Foster E (ed.) *Trans. Int. Vacuum Metallurgy Conference*. AVS, NY, pp. 719–37

Sutton W H, Maurer G E 1979 Influence of VIM crucible composition on the non-metallic content of an advanced hafnium bearing nickel-base superalloy. In: Bhat Slatter G K (eds.) *Proc. 6th International Vacuum Metallurgy Conference on Special Melting*. AVS, San Diego, CA, pp. 340–56

Winkler O 1960 The theory and practice of vacuum melting. *Met. Rev.* **5**(17), 1–117

Zanner F J 1979 Metal transfer during vacuum arc remelting. *Metall. Trans.* **10B**, 133–42

Zanner F J, Bertram L A 1985 Vacuum arc remelting—an overview. In: *Proc. 8th International Conference of Vacuum Metallurgy*. AVS, Linz, Austria, Vol. 1, pp. 512–52

F. J. Zanner

Encyclopedia of Materials: Science and Technology
ISBN: 0-08-043152-6
pp. 1–6