Update on Vacuum Melting Equipment

Initially a tool to meet superalloy requirements of very specialized industries, vacuum induction melting systems now produce tonnage quantities of high-performance materials for many applications.

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The steady growth in use of specialized materials, such as the superalloys, has required a steady development of processes to permit those materials to be "routinely" worked at a volume that is commercially viable.

Nickel- and cobalt-based superalloys must be consistent in their composition and reliable in the performance established for them. They must be capable of being processed at a cost which meets reasonable return on investment criteria.

Foundry practice over the past decade, utilizing developments in furnace technology, has made substantial progress in investment casting of superalloy material. The demands of the aircraft industry alone have given impetus to the development of production-scaled casting equipment to economically accommodate the special characteristics of superalloys while turning out a product that meets the required specifications.

Vacuum induction melting (VIM) is one of the major processing techniques used to produce superalloys. In many respects VIM, like the superalloys, is a relative newcomer to the foundryman's world, a development coinciding with commercial development of reliable vacuum equipment. VIM has grown as a production tool, initially to meet aircraft engine and turbine industry requirements, to the point that, today, VIM systems produce tonnage quantities for broad materials applications.

This paper will define and review the vacuum induction melting process and precision investment casting in general terms, concentrating on an update of vacuum induction melting with emphasis on the equipment involved and how it operates. It will examine state-of-the-art developments in vacuum induction melting furnaces and then take a brief look at what future developments might be.

VIM Advantages

Melting and alloying of a superalloy in a vacuum induction melting furnace produces a material, or alloy, of a higher density and purity than the original materials included in the melt. Castings are stronger, less porous and more consistent in quality from pour to pour.

Vacuum induction melting also allows handling of certain classes of metals that cannot be processed in any other fashion. Some exotic and refractory metals, if melted in a pure state or in open atmospheric furnaces, would vaporize or oxidize at temperatures below those required for actual melt and pour.

VIM is the preferred means for melting a pure metal alloy in a noncontaminating atmosphere. The major reasons for using vacuum induction melting are the elimination of inclusions in the castings, and the minimization of undesirable impurities in the material being melted.

This discussion deals with two types of inclusions. A solid inclusion is any foreign matter, such as a small piece of refractory, that would cause a flaw in the casting. Solid inclusions such as refractory material cannot be eliminated by vacuum induction melting. But impurities that may form inclusions during the casting process can often be removed by VIM. A second form of flaw or "inclusion" is a void in the casting.

The vacuum induction melting furnace removes solid impurities by withdrawal in gaseous form from the melt. In most cases, such impurities have a lower vapor pressure than the primary

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metal or alloy and will go through the molten and gaseous states, "outgassing" before the primary melt. Experience has shown that these outgassed elements will deposit somewhere in the system, such as the sidewall of the vacuum chamber or in the pumping fluid. Such deposition may continue for a substantial period before the deposits adversely affect the operation of the system.

Even in vacuum induction melting, working of some alloys becomes a complicated operation because of the dissimilarity of melting and vaporization points. One example of this is samarium/cobalt, an alloy used in manufacture of high gauss magnets for special applications such as aircraft instrumentation. Samarium has a much higher vaporization point than cobalt. Hence great care must be taken in vacuum melting to insure a sufficiently high base pressure during the alloying stage. In practice the cobalt is melted first under vacuum. Then the furnace is backfilled with inert gas and the samarium introduced again at sufficiently high base pressure during the alloying stage to inhibit vaporization.

The result of this carefully controlled process involving time, temperature and pressure is a uniform quality alloy melt that is used in producing high purity, homogenous samarium/cobalt magnets.

Equipment

Manufacturers of VIM furnaces provide a variety of equipment from which the foundryman may choose. The majority of vacuum induction melting furnaces used for precision investment casting, with the exception of billet manufacture of pure metals and alloys, are designed for 17-, 30-, and 50-lb capacities. These are semicontinuous systems. Batch furnaces in similar capacities are also available for precision investment casting.

The basic differences between batch and semicontinuous systems are briefly summarized as follows: In the batch furnace, it is necessary to open the melt chamber and insert the charge and molds and later remove the castings; in the semicontinuous furnace, the melt chamber is kept under vacuum at all times and the mold lock is cycled between vacuum and atmosphere.

The semicontinuous furnace is used for high production (see Fig. 1). A typical VIM semicontinuous furnace consists of a melt chamber containing the vacuum induction melting coil and crucible, a mold lock, mold lift, the necessary control components and two vacuum systems, one for the melt chamber and one for the mold lock. A special isolation valve (see Fig. 2) permits the mold lock to be cycled during loading and removal of the mold, thereby avoiding melt chamber contamination. The crucible is charged for the next cycle through an interlocked vacuum billet charging mechanism.

Fig. 1. Twin 50-lb capacity VIM furnaces form part of semicontinuous system for production melting.

The vacuum induction melting furnace system employs a vacuum melt chamber that is water-cooled. The induction coil is mounted inside the melt chamber so that it can be tilted to pour the melt. Enclosed by the induction coil is a crucible for containing the melt (see Fig. 3). The coil is connected to a high frequency induction power supply suitable for vacuum. The voltage from this power supply must be low enough to eliminate possibility of corona or arcing inside the vacuum chamber during the "power-on" or melting stage of the process. The reason is that in a vacuum chamber, air, the best insulator possible, has been removed, making conditions ideal for electrical discharge or corona to occur between coil terminations or the power leads and chamber.

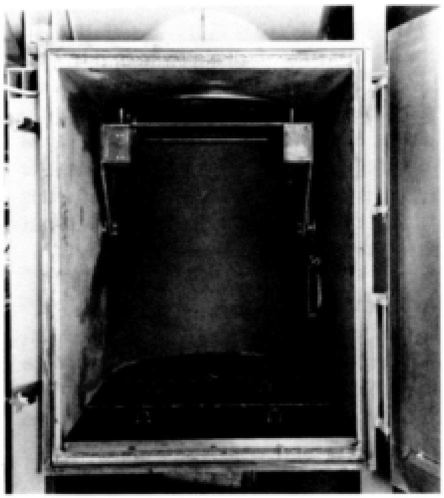

Fig. 2. An isolation valve permits the mold lock to be cycled during loading and removal of the mold, thereby avoiding melt chamber contamination.

Operating cycle time derives from a ratio between the power supply capacity and the size of the melt. With a 75kw power supply, for example, a 30-lb ferrous melt will take approximately 10 minutes. By contrast, with a 225kw power supply the melt will be accomplished in approximately 3 minutes. These estimates are based on utilization of pre-alloyed vacuum cast billets.

The frequency of the power supply is another consideration in a vacuum induction melting furnace. Most melting of ferrous charges in the 30 to 200-lb range is done in the 3000 to 1000-Hz range.

Selection of the power supply frequency is determined by the size of the melt, the basic rule being that the frequency varies inversely to the depth of penetration. As the size of the melt is reduced, for example, the frequency increases. (A lower frequency is not required because the depth of the penetration is less through the smaller coil diameter.) A larger melt (e.g., 3-5 ft in diameter) would probably require a line frequency of 60 Hz or 180 Hz. This insures good stirring action caused by lines of electrical flux cutting through the melt and creating continuous mass movement in the melt.

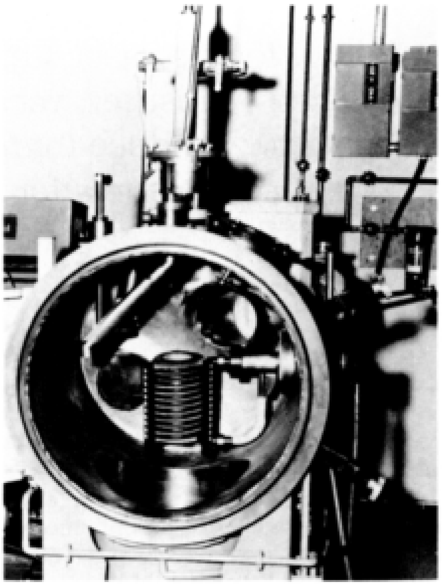

Fig. 3. The melt chamber for a 17-lb capacity VIM furnace.

There are several different materials such as aluminum oxide or magnesium oxide, from which melting crucibles can be made. If the melt involves copper, the crucible may be of common graphite. A pure graphite crucible is used and acts as a susceptor when it becomes necessary to melt by conduction. For example, in melting sapphire it is impossible to couple the magnetic lines of flux to something that is glasslike. Instead, the power is coupled to the graphite crucible first, and then radiated and conducted to the sapphire.

VIM Applicability

Applications for vacuum induction melting have been limited for several reasons. The "volatility" or instability of reactive metals and materials, when subjected to melting temperatures directly in open atmosphere, dictates that they be processed in vacuum or inert atmosphere. Reactivity of such materials with even the smallest percentage of atmospheric constituents could form undesirable oxides, nitrides or hydrides. These materials have been relatively scarce and have had limited applications. Their highly specialized uses, in small quantities, justified the higher cost of vacuum processing. Moreover, historically there has been little incentive to extend vacuum induction melting to include more common materials to improve their quality or performance because of the cost of vacuum equipment.

Now this is changing. Physical characteristics of some reactive materials such as zirconium, hafnium, titanium, etc, will always demand a vacuum to be safely processed. While these materials have remained scarce, and will probably continue to be so, applications for them have expanded and continue to broaden. The conservation of such material cannot be overlooked. Since vacuum is a "closed" process, elimination of scrap loss becomes an added advantage.

The performance of these materials has opened new markets. Where once their use was limited largely to high-performance aircraft engine parts such as jet turbine blades and vanes, new applications have developed. Examples of these are components for medical and dental devices.

Vitalium, for example, a cobalt-based alloy, is used in increasing amounts for manufacture of prosthetic devices. These include heart valves, hip joints, dental implants, pins for broken bones, and other such examples. These products, and others yet to come, require special alloys that to date have proven to have virtually no rejection reaction when implanted in the body.

Vacuum melting and casting, in general, is becoming more attractive because of its cost effectiveness as a day-to-day production method compared with atmosphere melting and casting. This is especially true of the more expensive materials processed in vacuum. In some cases, however, vacuum melting and casting of specialty steels is also becoming more commonplace.

There is an increasing investment burden placed on the metals processor to comply with pollution legislation as well as worker safety regulations. When such investments—in many cases at extremely high costs—have been met, the metal processor still has only achieved a way of obtaining a product with the same properties and characteristics as in the past. This is not the case with vacuum processing.

It is generally true that with vacuum equipment the initial capital investment is higher. This is simply because it is necessary to have additional mechanical and electrical systems to permit vacuum processing. But vacuum furnace equipment does not produce vapor or liquid effluents requiring disposal into the environment. Other types of furnaces do. There is no additional cost for environmental protection equipment or worker safety equipment with vacuum as is generally the case with other types of melting furnaces.

Vacuum furnaces are more energy efficient, since, in general, they can be raised to temperature on demand instead of having to be maintained at an "idling" temperature between melting cycles.

Another major factor favoring vacuum induction melting and casting is that a better product is produced. The benefits may be in the form of a brighter finish, more consistent physical characteristics, etc. Many such characteristics, of course, can be obtained by air melting with additional processing steps, but this means more production time, more production personnel and additional equipment—all of which add up to a higher cost of turning out the product.

Advances in Control

Electronic advances in the state of the art in vacuum induction melting furnaces have been significant. Modern VIM systems are being built with a wide variety of solid state electronic controllers incorporating highly versatile programmable controllers, electronic temperature sensing equipment and solid state induction melting power supplies unknown in the industry only a few years ago. Single VIM systems are being "ganged" so that fewer personnel can operate larger facilities and still obtain the same product with the same qualities, cycle after cycle, in greater quantities, with the use of programmable controllers and computer techniques.

Right now, for example, a programmable controller and microprocessor-controlled vacuum induction melting furnace for melting ferrous alloys is available that will be operated from a central plant some distance from the furnace facility. It is being used for superalloy application and is an example of what can be done in an otherwise normal production situation.

Computer control of the vacuum induction melting operation is the coming trend. There is no doubt that within the next several years we will see an installation consisting of a bank of perhaps 20 electronically controlled vacuum induction melting furnaces. The operator will merely monitor the operation from a central display panel while a central data processing and control system actually provides the signals to load the furnaces, cast the mold, pump down and run all the equipment around the clock if desired.

One application for VIM types of furnaces is directional or controlled solidification. The technique uses controlled cooling of a vacuum induction melted casting to produce a high-strength oriented crystal alloyed part. Solidification of the material is controlled so that the investment casting consists of oriented grain boundaries that result in a part with superior ductility and thermal shock resistance, increased axial strength, and greater creep resistance. High performance jet engine parts such as turbine blades are produced by this process.

Now the technique has been pushed even further. This was described recently in an article on advanced materials appearing in *Aviation Week & Space Technology*, Oct 1, 1979, which reported use of single crystal technology in the manufacture of turbine airfoils. The technique, pioneered by Pratt & Whitney's Commercial Products Division, is expected to yield even higher performance in jet engines over that obtained with directional solidification. According to the report, the single crystal technology results in a cast blade of a single metal crystal having no grain boundaries. This, in effect, eliminates additional elements required in directional solidification to maintain grain boundaries. The result, the article concludes, is a single crystal alloy with optimized creep strength and resistance to thermal fatigue, oxidation and hot corrosion.

The limit of application for vacuum induction melting certainly has not been reached. New applications are being studied and more will come from the industrial and academic laboratories.