MELTING SYSTEMS FOR PRODUCTION OF TITANIUM INGOTS AND CASTINGS

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Titanium melting has made considerable advancements since commercial titanium production began in the mid to late 1940's. During the 1950's, a great deal of research and development was conducted by a number of research institutes and metal producers.

In an effort to develop efficient processing techniques, almost all of the available melting know-how was exploited. But due to the reactive nature of this emerging material, it was necessary to provide an inert atmosphere for melting along with a non-reactive crucible. Consequently, early melting practices were conducted under argon or helium atmospheres using non-consumable arc electrodes of either tungsten or carbon. And although some of the original tests were conducted using small water-cooled platinum crucibles, these were rapidly replaced with water-cooled copper crucibles which, of course, is our standard today.

Due to the inherent contamination from carbon and tungsten electrodes, the consumable arc melting process was soon adopted. Also, to improve the quality of titanium ingots, the practice of melting in a vacuum soon replaced melting under positive pressure of inert gas. These developments led to what we now refer to as the VAR or vacuum arc remelt furnace which, unquestionably, is a rather incorrect description of the equipment when it is used for the primary melting of titanium.

Although this technology has evolved considerably over the past 30 years, the VAR furnace is still the workhorse for producing titanium ingots and castings. However, due to the continuing requirements for both quality and cost improvements, other melting processes are slowly gaining acceptance and being used to produce finished titanium ingots from sponge, alloy, and scrap.

Presently, the processing technologies used most extensively are non-consumable or Rototrode melting, electron beam melting and transferred arc plasma torch melting. Another system worth mentioning is the inductoslag process which is being used in a number of development applications but has not yet been applied commercially.

I am breaking this presentation into two parts: Part I deals with the primary melting of titanium and Part II deals with the remelting of titanium as most titanium melting for quality applications requires a double or even triple melt procedure to insure proper homogeneity in the ingot.

At this point, I would like to discuss Part I - The primary melting of titanium using titanium sponge, alloying elements, and a variety of scrap forms enabling maximum recycling capability and optimizing the economy of producing titanium ingots and castings.

1. The most popular system presently employed for primary melting is the consumable electrode (VAR) vacuum arc melting furnace. For this system, electrodes are formed by pressing blended sponge and alloy in compacting dies to form briquettes. The size and shape of the briquettes may vary with electrode size requirements and, of course, the press available for compacting. Figure 1 shows a variety of compact shapes which are used in titanium production.

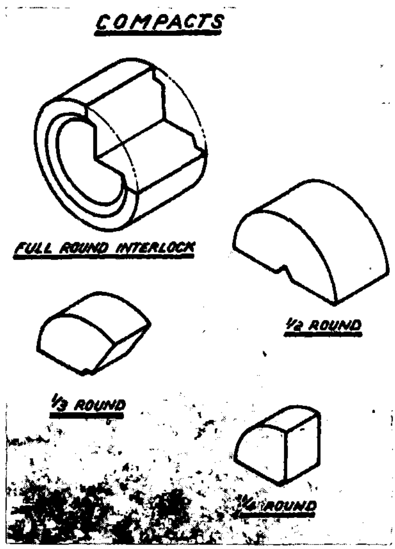

Fig. 1: Titanium sponge compact configurations.

These compacts are then assembled into an electrode (Figure 2) which, in this case, is tied together with a central tie rod. The electrode assembly is then placed on an electrode transfer cart which moves the electrode into a plasma welding chamber (Figure 3). In this chamber, the electrode is welded into a structure having both sufficient mechanical strength and electrical continuity to enable primary melting into a first melt or primary ingot. The more modern welders are automatically cycled through the entire welding process by a programmable controller (Figure 4).

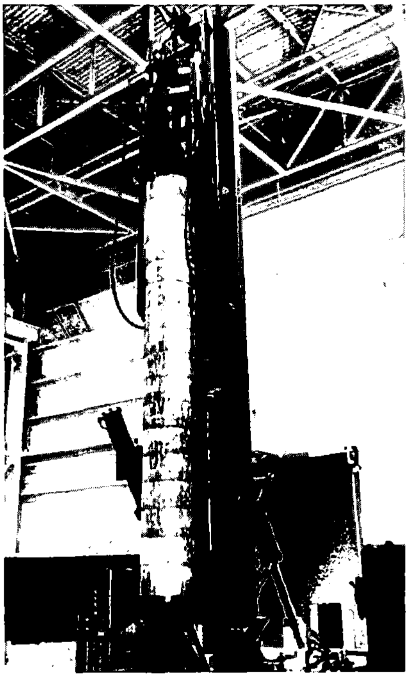

Fig. 2: Electrode assembler.

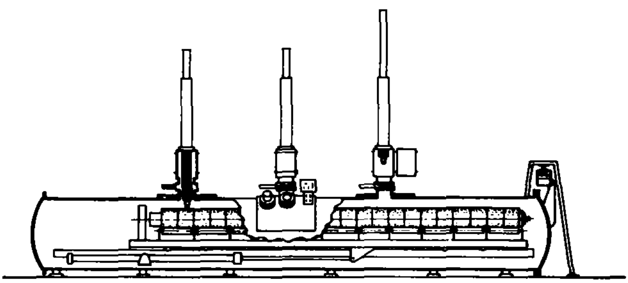

Fig. 3: Plasma electrode welder schematic.

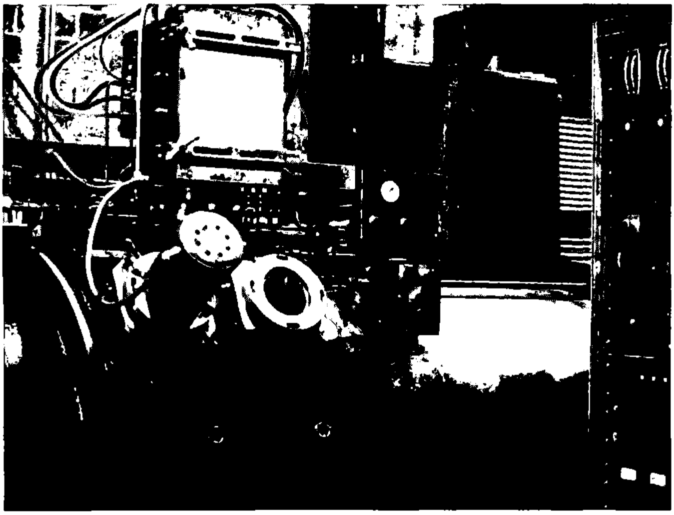

Fig. 4: Plasma welder illustrating welding station and process controller

Due to the ever increasing performance demands on titanium, procedures for electrode production are becoming more stringent, especially concerning the highly stressed parts required for aerospace applications. Because of this, electrode welding has evolved from heliarc welding in air to mig welding in air, followed by plasma welding in air to today's plasma welding chambers, which minimize low density inclusions by reducing oxygen and nitrogen titanium contamination.

After electrode preparation, the electrode is moved to a consumable arc melting furnace to enable primary melting. Figure 5 shows a typical VAR furnace. Figure 6 depicts the cross section of the primary consumable vacuum arc melting furnace, showing the major components, consisting of the following:

a. Furnace Column
b. Furnace Head
c. Furnace Ram and Electrode Clamp
d. Furnace Throat
e. Furnace Crucible
f. Furnace Water Jacket
g. Consumable Electrode
h. Water Jacket Assembly
i. Vacuum System

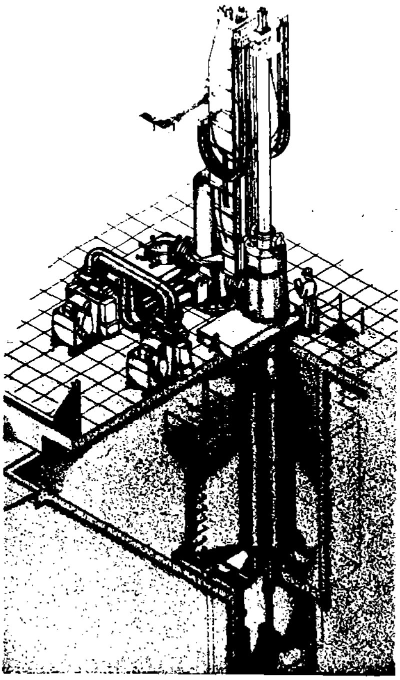

Fig. 5: Vacuum arc remelt furnace isometric rendering.

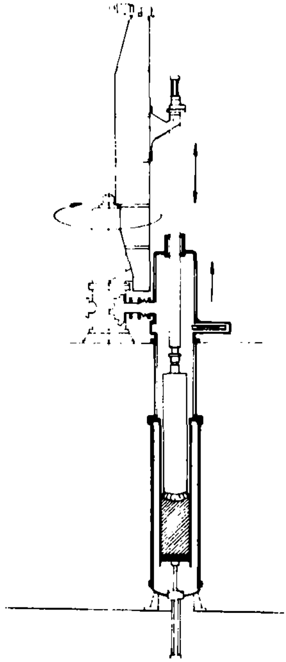

Fig. 6: Vacuum arc remelt furnace schematic.

In primary melting, the arc is usually struck to either a small pile of sponge or a briquette of suitable size and shape. As soon as melt stability is obtained, power is increased to melt level requirements. Power requirements for primary melts in consumable electrode type furnaces are usually governed by the diameter of the crucible and the electrical integrity of the electrodes being melted since most of the conducted current in primary electrodes must be carried through the welds.

2. Figure 7 shows an isometric view of a modern non-consumable arc melting system. This equipment utilizes the Rototrode, a rotating, water-cooled copper electrode which is usually mounted angularly to the melt pool. The Rototrode is coupled electrically and mechanically to an arc generating surface, and the electrode functions without being consumed by the melting arc because of a phenomenon called arc locking, and because of the ability of the arc generating surface to be in continuous motion relative to the arc itself.

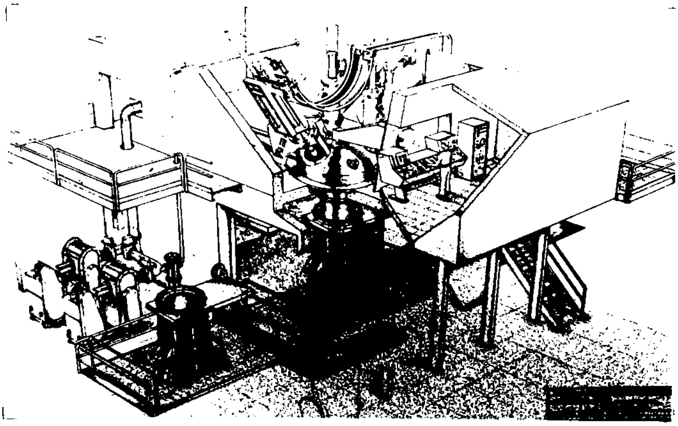

Fig. 7: Non-consumable Rototrode arc melting furnace isometric rendering.

The Rototrode itself (as shown in Figure 8) is moved about on a large vacuum ball joint to reach all areas of the molten pool. This is accomplished by servo control of the X, Y and Z axes. The X and Y axes are normally controlled by the operator and the Z axis is controlled by automatic control of the arc voltage. As you can see in Figure 9, the melt chamber funnels into the melting crucible cavity. This design has two major advantages: the first is to funnel all material into the crucible, even feedstock, which may be thrown out of the crucible by the rotating electrode; the second is the easy cleaning of the melt chamber.

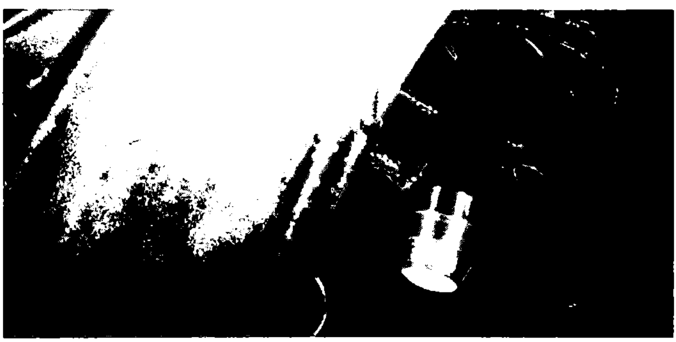

Fig. 8: Water-cooled copper non-consumable roto-trode tip.

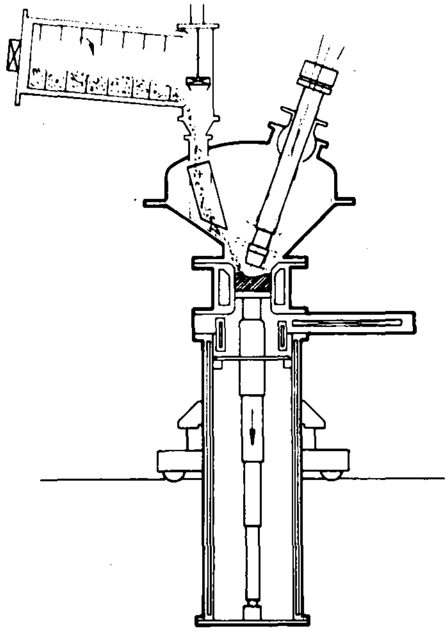

Fig. 9: Non-consumable Rototrode arc melting furnace schematic.

In this configuration, the material is fed from two rotary feeders down to a chute and onto a feeder plate, where the material is then pushed into the melt zone with a bulldozer. When small materials such as sponge and chips are fed, the chute is maintained partially open to allow this material to go directly into the pool.

As the ingot is formed, it is withdrawn into the ingot withdrawal chamber by means of a mechanized, water-cooled puller. This system is designed to prevent over-stressing the crucible and water jacket system when withdrawing the ingot. Upon completion of the melt, the withdrawal chamber is valved off from the remainder of the system and moved to an unloading station for removal of the first melt ingot.

To date, equipment of this design has been built to accommodate ingots 800 millimeters in diameter and up to 4.5 meters in length. As sizes progress beyond this range, we will have to review the possibility of using multiple electrodes.

3. Figure 10 shows an exterior view of a production size electron beam melting furnace that is used for melting a variety of scrap into primary ingots. This unit combines a hearth melting system with a withdrawal type crucible and can produce both cylindrical and slab type ingots. In the hearth melter, the feed material is pre-melted prior to entering the crucible. This permits the precipitation of high density inolusions before the molten metal enters the withdrawal type ingot mold.

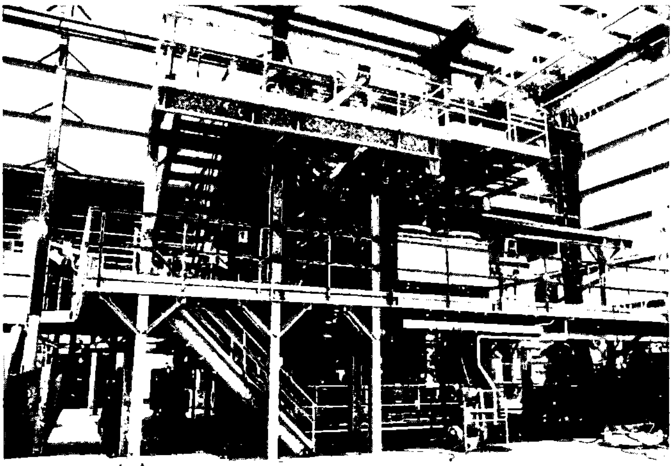

Fig. 10: 2 megawatt Electron Beam melting furnace.

In this application, multiple guns are used with two or three guns melting the material in the hearth and another gun heating the ingot surface. As the melt progresses, the ingot is withdrawn into the ingot withdrawal chamber, which has an isolation valve similar to the non-consumable furnace. This type of equipment is capable of melting both round and slab type ingots because of the mobility of the electron beam. Although electron beam melting of titanium is most adaptable to the recycling of commercially pure scrap, a considerable quantity of alloy material has been and is being melted by electron beam. Correction for alloy degradation is handled in a subsequent VAR melt by additions of alloy or alloy and sponge to make up for the evaporative losses due to the high vacuum environment of the E.B. furnace.

4. Plasma melting equipment for titanium processing is now coming into its own. Japan has used plasma for several years and, at the present, two production melting units

are in operation in the United States, both using single torches in the range of 600 KW plus.

The torch system used for melting of titanium is a modification of the Union Carbide torch. Its most outstanding feature is that it incorporates a hollow, cylindrical electrode which is constructed of copper with a graphite liner. This torch nominally operates at 200 VDC and 3,000 amps plasma current in the transferred mode, and it is mounted on a ball joint similar to that discussed in the description of the Rototrode. Movement in the X, Y and Z axes is hydraulically actuated.

Prior to operation, the melting chamber is evacuated by mechanical blowers and checked for leaks before being back-filled with argon to a slightly positive pressure. The arc is then initiated and melting commences in a manner similar to that described in non-consumable melting. Figure 11 schematically shows a vertical plasma melter. You may notice that material feeding and withdrawal of the ingot is the same as that used for non-consumable melting.

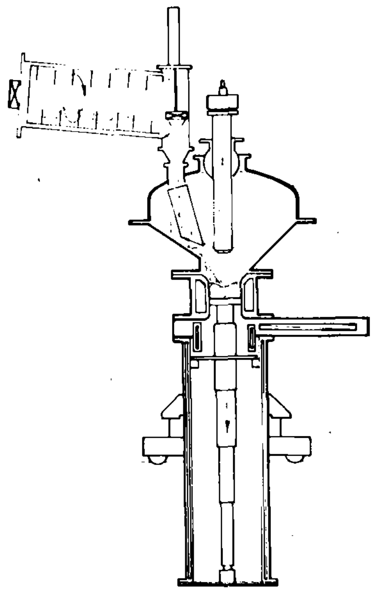

Fig. 11: Vertical plasma melter schematic.

Another approach to plasma melting and consolidation is using a horizontal chamber which is approximately 15 meters in length. With this unit (Figure 12), a horizontal trough of water-cooled copper is fed material via a rotary drum feeder. The melt cart is moved mechanically below the torch flame and the contents of the melt trough are fused together or completely melted depending on the composition of the scrap and raw material charge.

Fig. 12: Horizontal plasma melter interior illustrating water-cooled copper trough, material feeder and 600 KW plasma torch.

5. I would like to mention the inductoslag melting system at this time as it is an emerging technology. Developed by Phil Clites at the U.S. Bureau of Mines in Albany, Oregon, this system involves induction melting of titanium by the unique combination of a water-cooled, segmented crucible and a high purity calcium fluoride slag. Figure 13 shows a withdrawal type unit that was used in melting a variety of titanium and zirconium scrap.

   To date, the largest unit that has been successfully operated incorporates a 20 cm diameter crucible and a 300 KW induction power supply. This furnace is built to operate both in the withdrawal mode and as a skull caster. A dual chamber design permits finished castings to be removed from the mold chamber without interrupting melting operations in the main furnace chamber, and a vacuum locked rotary material feeder allows the continuous charging of a variety of scrap. Although this system has not yet produced any tonnage results, it certainly has the potential to do so.

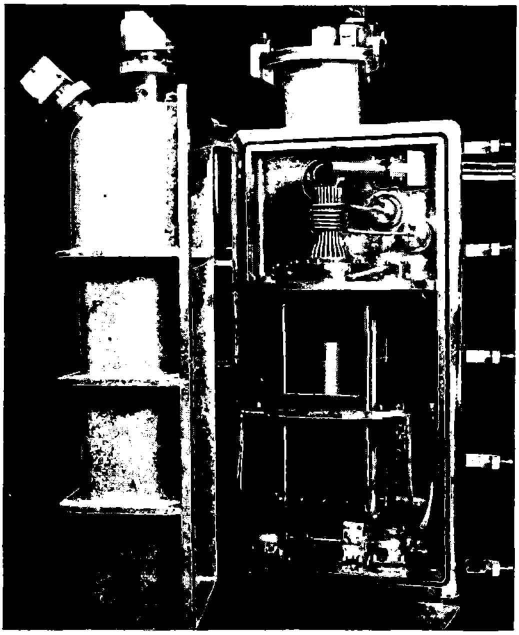

Fig. 13: Inductoslag casting furnace.

The foregoing describes those systems which are currently being used for the commercial primary melting of titanium. I would now like to discuss those systems being used for secondary and tertiary melting operations for finished titanium ingots.

1. The VAR furnace indicated in Figure 14 is the basic equipment used for ingot production. Since I have already mentioned the mechanics of this system, we will concentrate on the latest state of the art controls being used to control final ingot melting. Today's state of the art controls include a dedicated computer and data acquisition system to enable the ultimate in melt control and melt data recording. Similar types of control systems are used by all major furnace builders to enable the simultaneous control of all the factors so important to manufacturing maximum quality, maximum yield titanium ingots. One of the difficult factors encountered in providing a user friendly computer control system is the expense of developing software for a relatively confined market. However, the ever increasing stringent requirements, especially as related to the aerospace industry, is forcing this requirement.

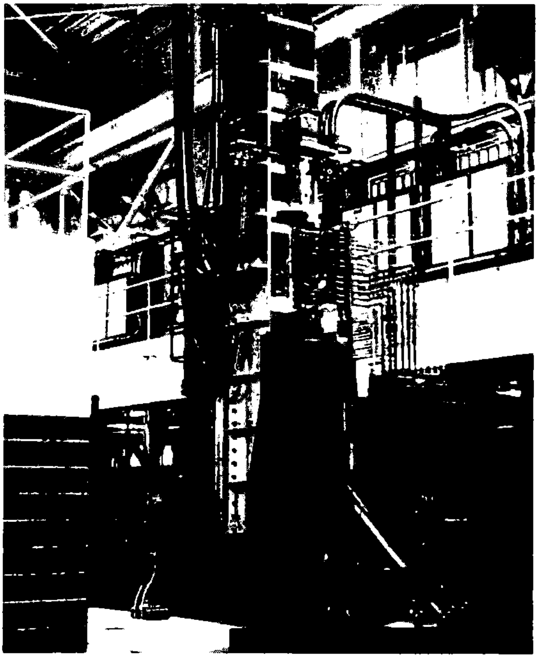

Fig. 14: Vacuum arc remelt furnace.

The heart of this particular system is an HP 9836 mini-computer, including a data acquisition module and a Winchester disc drive. Depending upon the program which is used, and the characteristics of the particular material to be melted, the furnace can be controlled in a variety of modes. In addition, various melt profiles may be selected and the chosen program is followed by the furnace controls. If the actual program does not match the profile, one or more factors may require attention, such as crucible cleanliness, metering accuracy, etc.

In melting titanium, two common melt modes are normally used: arc voltage control and drip short control. However, these modes only control the electrode positioning. Melting speed, hot topping, stirring conditions, vacuum level and other melt variables are controlled by the computer. All data which is not graphically displayed on the computer screen is updated continually and printed out in a digital display on the CRT. After a melt has been completed, all melt data is available from a magnetic tape. The actual melt profile on the screen can then be printed out on a thermal printer, providing a permanent record of the melt.

As you can see, as new alloys are developed or ingot dimensions change, the ultimate program can be developed and put into the system. Of course, as you may already know, the computer is also an invaluable tool for trouble-shooting equipment requiring maintenance. In the case of the furnace described here, any trouble that occurs is printed out on the CRT. We could discuss the details of the control system for hours, but I would like to proceed in discussing other systems for the final melting of titanium and casting applications.

2. Electron beam melting has been used for remelting titanium, but primarily commercially pure material. Electron beam remelting can be accomplished by drip melting as shown in Figure 15 by secondary hearth melting a second time, or if desirable, by side feeding.

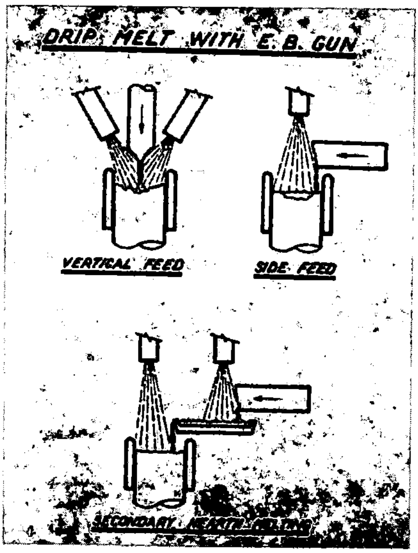

Fig. 15: Electron beam melting configurations.

3. Plasma melting for finished ingot production is also a possibility by employing side feeding of the first melt electrode. However, this system may not be practical when considering large size ingots.

To conclude this presentation, I will briefly discuss melting systems which are presently being used for casting titanium into finished parts and shapes.

Figure 16 shows the assembly of a large casting furnace incorporating a centrifugal casting chamber and a consumable electrode feed into a tiltable casting crucible capable of casting 1,000 Kg of titanium. Such systems are the most common in the casting industry today and are really the workhorse of the industry. They vary in size from two kilograms pouring capacity to units similar to that shown in the figure.

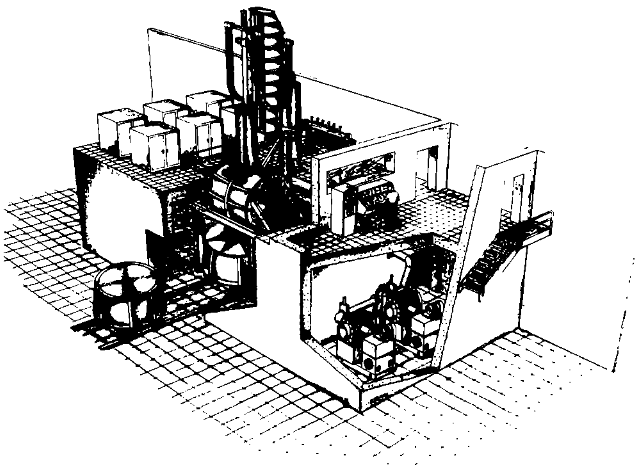

Fig. 16: VAR centrifugal casting furnace isometric rendering capable of casting 1,000 Kg of titanium.

Some limited casting has been done with non-consumable electrode units as shown schematically in Figure 17. However, this method of casting has not yet gained very popular support for several reasons:

a. It requires chemistry on material.
b. The expense of equipment.
c. It cannot provide as big a pour with existing technology as can be obtained with VAR melting.

The inductoslag casting furnace shown in Figure 18 is being used in a limited application. This unit is capable of casting approximately 25 kilos of metal per heat and is being used for the production of commercial grade castings. Although the equipment was first used as a development tool, it is now producing quality commercial castings.

It was my original intention to include a chart relating the energy efficiency of various melting systems. However, this can be a very controversial subject as there are many variables that can affect the numbers. For this reason, I decided

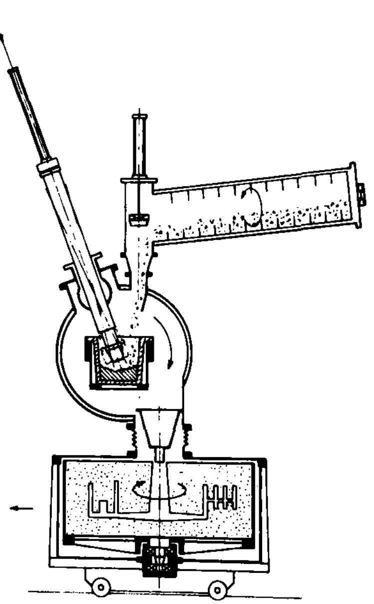

Fig. 17: Non-consumable roto-
trode centrifugal casting
furnace.

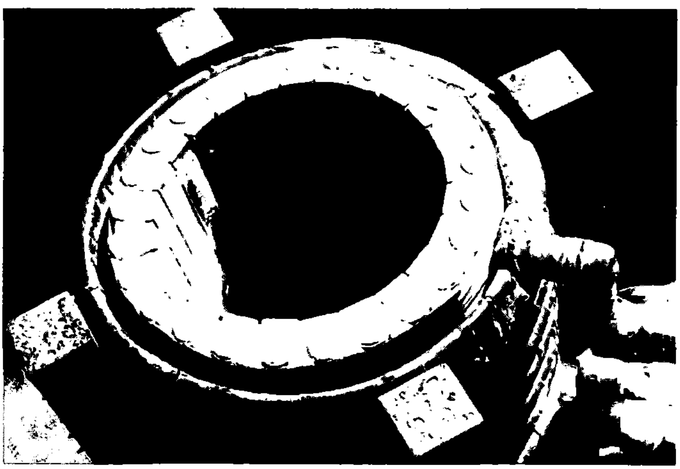

Fig. 18: Water-cooled copper inductoslag finger
crucible.

to eliminate this from the presentation.

In discussing new directions of titanium melting, there is of course a great deal of development that can be accomplished with the systems we have reviewed. There is also a great deal of work to be done regarding hybrid melting systems which will combine two or more melting technologies to adapt processes to a given alloy requirement and to minimize the many handling steps that are presently required.

For example, I believe that with today's technology, it is possible to start with sponge, alloy and scrap and melt to a finished ingot using a combination of cold wall melting technologies to accommodate the special requirements of titanium and its alloys.

There is still a tremendous amount of work to be accomplished in optimizing the production of finished titanium ingots from raw materials. It is apparent that the next generation of titanium practitioners has their work cut out for them; not only related to alloy development, forging, rolling and other downstream processing, but to the tremendous opportunity to upgrade both process and equipment for the melting of titanium and its alloys.