THERMAL MODELLING OF SOLIDIFICATION AND COOLING OF AN ELECTRON BEAM MELTED TITANIUM INGOT

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Abstract

Electron beam remelting ("drip melting" or "cold hearth refining") is a technique which is frequently used for the production of titanium alloys. In order to describe the thermal behaviour of the remelted ingot, a mathematical model has been used. The model, which involves a numerical solution of the heat transfer equation in the ingot during its growth, calculates the temperature distribution in the ingot, the profile of the melt pool, the overall heat balance and the weight losses due to evaporation of liquid metal, for all stages of the remelting operation. The results of melt simulations are presented and discussed. The effect of variations in the operating parameters (melting rate, gun power, beam focusing) is described.

Introduction

Over the last decade, the increasing demand for high purity ultra-clean titanium and titanium alloys has led to a growing interest in the electron beam remelting process (1). Two remelting processes, employing one or more electron guns, are in use today:

- the discontinuous "Drip Melting" technique, in which a primary ingot is melted by the electron beam(s), the resulting metal droplets forming a secondary ingot which solidifies in a water-cooled copper crucible,
- the continuous "Electron Beam Cold Hearth Refining (EBCHR)" process, involving a purification and inclusion separation stage in a cold hearth furnace before ingot formation.

The present paper treats this secondary ingot formation stage, which is common to both processes. Mathematical modelling represents a powerful tool for analyzing and optimizing the process, which involves numerous interdependent physical phenomena, and where an experimental approach is difficult, due to the high temperatures attained. The study carried out at the School of Mines in Nancy, which is presented here, is based on the development of a thermal model of the secondary ingot and its application to the remelting of titanium.
Conclusion

Electron Beam Cold Hearth Refining has experienced substantial growth over the past four years in capacity, quality, and commercial acceptance. Many applications such as hollow ingot casting, improved scrap recycle techniques, and more efficient sponge melting are to be expected in the next four years.

References


Development of the EDX system was suspended in 1990 in favor of a twin wavelength spectroscopy system being developed at Forschungsgesellschaft für Elektronenstrahl und Plasmatechnik mbH (FEP), a former division of the Manfred Von Ardenne Institute in Dresden, Germany. The twin wavelength x-ray monitoring system (TXM) measures the intensity at two pre-selected wavelengths in the x-ray spectrum. One wavelength is a characteristic wavelength of the element of interest, such as Al or Cr, and the second wavelength is part of the background, or bremsstrahlung, radiation. The ratio of the intensity at these wavelengths can be correlated to the chemistry of the molten pool using a package of custom software. The system was described in more detail by N. Schiller in a paper at the 1991 Reno EB Conference. (7)

Axel Johnson Metals has joined with FEP and Bakish Materials Corporation to continue the development and installation of the first industrial TXM system. These three organizations have also executed a commercial agreement for the marketing and distribution of similar systems.

Condensate Control

The term "condensate" is usually given to all types of deposits which form on the internal walls and structures of the vacuum chamber in an EB furnace. The management of condensate has been an issue since the early days of electron beam melting.

Although often described by the same term, "condensate" really takes two primary morphologies. The first type is the classical form in which evaporating species leave the molten bath in the gaseous state and travel to cooler structures within the vacuum chamber where they condense to a solid coating.

The second type of deposit is not related to evaporation from the molten bath. This type of deposit would be more accurately described as "spatter" since it results from the ballistic transfer of small liquid and solid pieces of the raw material from the melt zone to the walls and overhead screen. This type of deposit is most commonly caused by the explosive release of trapped gases and chlorides from titanium sponge which has not been vacuum distilled.

Various strategies have been developed over the years for dealing with both true condensate and spatter. The most common and most successful strategies have been to provide an overhead screen and other similar places to collect and retain the deposits and to control the selection of raw materials charged into the furnace. Advances have been made in recent years in such areas as screen design and construction, the installation of vertical spray shields, and the usage of higher proportions of vacuum distilled sponge. These changes, while certainly helpful, have been gradual in nature. Efforts are now underway to identify and implement breakthrough technologies to provide a major improvement in condensate management. Techniques now being studied include dynamic removal of the deposits between ingots by thermal shock, vibration, and melting. Furnace operation at increased pressure (100 µm) is being investigated to attempt to reduce evaporation along with carefully programmed electron beam energy distribution and liquid metal surface temperature monitoring. The interior geometry of the furnaces is being evaluated and modified to minimize the area of condensing surfaces close to the liquid metal including such developments as low profile hearth and mold configurations. Melting techniques are also being developed to continually recycle (reflux) spray deposits from sponge as they occur in the melt area.
AJM acted as general contractor for this installation using Retech, Inc., for mechanical components and Innotech, Inc., for power supplies and controls for the Von Ardenne electron beam guns purchased from Bakish Materials Corporation. Local contractors erected the furnace. Assembly of the furnace started in January, 1990 after one year of engineering and fabrication. The first ingot was cast in September, 1990 with commercial operation following immediately, Figure 5.

![Figure 5. Side view of MaxiMelt dual chamber furnace.](image)

The "MaxiMelt" or "B" furnace was designed for a nominal 4500 MT (10 million lbs.) per year capacity (varies with product mix) which together with the smaller "A" furnace provides a nominal 6800 MT/year (15 million lbs./year) of EBCHR capacity in the AJM melt shop.

### New Developments

**On-Line Chemistry Control**

During the Sixth World Titanium Conference and at subsequent events, a system for on-line, real time chemical analysis based on energy dispersive x-ray (EDX) spectroscopy was described. (1) This system had worked well during laboratory trials and there was reason to believe it would also be successful in an industrial environment. Unfortunately, several problems were experienced which greatly retarded the further development of the system. These problems included the high number of back scattered and secondary electrons which are present in large industrial furnaces and the small fluctuations in beam focus and location caused by small (approximately 5 μm) pressure changes in the furnace atmosphere.
Figure 3. Schematic drawing of 3.3 megawatt, dual chamber MaxiMelt electron beam furnace.

Figure 4. Overhead view of "C" shaped hearth and mold geometry containing solidified titanium skull. Melt zone is at top of photo, refining hearth is on left side; empty slab mold is at bottom.
The "clean titanium" EBCHR process has grown commercially since 1988 extending to advanced alloys such as Ti-17 as well as to Ti-6Al-2Sn-4Zr-2Mo. The process is being more widely accepted following the FAA report on the titanium industry after the Sioux City DC-10 crash. (3) Much has been learned about optimizing the process by using special furnace geometries, heat and flow patterns, and sensors. The EBCHR process has recently been joined commercially by a plasma torch heated hearth melting process (PAM). (4)

Over 2,700 MT (6 million lbs.) of hearth refined "clean titanium" has been produced to date. In response to this increased demand, a new 3.3 megawatt EBCHR furnace has been built and qualified at AJM's Morgantown, PA, USA facility. (5) All indications are that hearth refining (EB or Plasma) will be used to process most titanium alloys for premium quality aerospace applications in the future.

MaxiMelt

The capacity of the 2 megawatt EBCHR furnace which AJM brought on stream in 1983 had been reached by 1988. It was time to design a new furnace. A market review indicated the need to scale up the existing furnace by about 50%. The resulting design featured 3.3 megawatts of power with three 600 kW and two 750 kW EB runs, six 50,000 liter/sec diffusion pumps, and a larger ingot and slab casting capacity. New mold sizes included a 508 x 1524 x 4699 mm (20 inch x 60 inch x 185 inch) mold for titanium slabs weighing 16.4 MT (36,000 lb.) and a 914 mm diameter x 4699 mm (36 inch dia. x 185 inch) mold for titanium ingots weighing up to 13.6 MT (30,000 lb.). (5)

The overall layout of the furnace uses two melt chambers so that while one chamber is in production, the other chamber can be cleaned out and maintained, Figure 3. The power lid can be easily switched from one chamber to the other as can the pumping, feeding, and casting systems. The melting chambers are large enough, 4m (13 foot) diameter, to allow a large patented "C" shaped refining hearth geometry and spray baffle to be optimized for producing hearth refined "clean" titanium, Figure 4. (6) A computerized beam energy distribution system is utilized to provide maximum flexibility and memory recall of preset distribution programs.
To further enhance as-rolled surface quality, belt sanding was introduced as an option in early 1991. A typical belt sanded surface is similar in roughness to a "precision machined" surface. Belt sanding can be used independently of or in conjunction with machining.

Today, surface conditioning can be tailored for specific customers and their processing requirements. A wide variety of conditioning options are available and are routinely delivered.

The Clean Alloy Titanium Program

Electron Beam Cold Hearth Refining has been used for many years to remove high density inclusions (HDI) from titanium scrap. The inclusions such as tungsten welding electrode tips, molybdenum or tantalum fasteners, or tungsten carbide tool bit pieces sink into the skull of solid and mushy titanium contained in the cold water cooled copper hearth as the liquid metal flows over the hearth. (2) In 1984 General Electric Aircraft Engines approached Axel Johnson Metals to investigate the removal of low density inclusions (primarily titanium nitrides) by EBCHR using AJM's 2 megawatt furnace. The subsequent development efforts included many melting trials in which the furnace geometry and melting parameters were varied and tested by melting feedstock which had been seeded with known high interstitial defect (HID) formers. This work resulted in a commercial process to produce "clean titanium alloy" as reported at the 1988 titanium conference, Figure 2. (1)
Cast Titanium Slabs

One of the first titanium products produced in commercial volumes by EBCHR was cast slabs. These slabs represented an early form of near net shape casting since they avoided the forging or cogging step required to convert a round ingot into a rectangular slab suitable for flat rolling. These products have steadily gained acceptance in nearly all flat rolled markets and millions of pounds are produced yearly.

Mold Development

A 150 x 965 mm (6 x 38 inch) slab mold was first used by Axel Johnson Metals (AJM) in 1983. These slabs were intended for direct rolling to plate or coil. Maximum slab weight was about 2.5 MT (5,400 lbs.), although the practical limitation was about 2.2 MT (4,800 lbs.) due to certain size restrictions for cross-rolling at some rolling mills. The maximum as-cast weight in the mold was limited by the size of the casting chamber and therefore limited coil applications due to economic reasons.

In an effort to provide more weight, a 305 x 1120 mm (12 x 44 inch) slab mold was introduced in 1985. These slabs weighed up to 5.7 MT (12,500 lbs.) and made the rolling of coils more economical. The 305 mm (12 inch) thickness also permitted greater rolling reductions for heavier gauge plates. The cross-section of the product was limited at the time not by a particular metallurgical reason but by the physical capabilities of the original Axel Johnson Metals electron beam furnace.

In 1991, the commissioning of the second EB furnace at AJM allowed the opportunity to install a 150 x 1270 mm (6 x 50 inch) slab mold in addition to the continuing use of the older two sizes. The maximum length of the cast slabs was also increased from 3,780 mm (149 inches) to 4,700 mm (185 inches). These wider and longer products opened new opportunities for direct coil rolling as weights of the conditioned slabs exceeded 4.1 MT (9,000 lbs.).

The goal of a 4.5 MT (10,000 lb.) conditioned thin slab for direct coil rolling was achieved in 1992 with the installation of a 178 x 1270 mm (7 x 50 inch) mold. Examples of these new slabs are seen in Figure 1.

Heavy slab evolution also progressed with the purchase and installation of the current jumbo mold for 305 x 1575 mm (12 x 62 inch) slabs. These slabs, with weights up to 9.1 MT (20,000 lbs.) were developed to avoid the necessity of cross-rolling for wide coils and to provide extra weight for heavy plates.

Surface Conditioning

Conditioning practices for the as-cast slabs have also evolved over the years. The first cast slabs were machined on the major surfaces using a horizontal planer to a surface finish of about 4.4 µm (175 microinches) RMS. Most rolling practices at the time included an intermediate break-down stage at about 75 mm (3 inches) with the opportunity to inspect and grind any residual surface defects.

As the applications for the slabs broadened, new conditioning practices were also developed. Some demanding applications such as the direct rolling of hot band from 305 mm (12 inch) slabs required a better surface finish than 4.4 µm (175 microinches) since the opportunity for an intermediate inspection and conditioning had been eliminated. For these cases, a "precision machined" surface finish was developed. This machining practice involved planing a 1.3 µm (50 microinch) RMS surface on the major surfaces, the sides, and the edges. The precision machining, combined with dye penetrant inspection greatly improved the surface quality and the finished yield of the products.