VACUUM SYSTEMS FOR TITATIUM REFINING:
A REVIEW OF THE LATEST VACUUM PUMPING TECHNOLOGY

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Abstract

The major processes for refining and purifying titanium, in preparation for its use in manufacturing specialised components for the high technology industries, are dependent on keeping the material isolated from the atmosphere under a vacuum. This is necessary to avoid unwanted high temperature reactions with, and contamination by, air gases during refining. The vacuum systems required to operate such processes must be configured and optimised not only to suit the particular vacuum performance needed, but also to deal with the specific challenges to the pump system arising in each case. This paper reviews the latest developments and techniques in vacuum pumping systems applied to the two main titanium refining processes, vacuum arc refining and induction skull melting.

Introduction

The importance of titanium and its alloys as a key constructional material for high-specification components remains vital in the world-wide high technology industries such as aerospace, power generation, chemicals, and others. In recent years there has been increasing investment in extracting, producing and refining this important metal, and there has been continuous development of new titanium alloys and new applications, especially in locations where the material availability, manufacturing expertise, and high technology users all co-exist, such as the CIS nations. The recent condition of this market in particular has been well reviewed by Ivasyshyn and Aleksandrov [2]. However, it is important to note that simultaneous developments have been continuing in areas of equipment technology, which are also contributing to the improved efficiency of the refining processes and so increasing the availability of affordable titanium alloys for further expansion of its applications. The major processes of vacuum arc refining and more recently induction skull melting have benefited from the continuing development of vacuum pump technology, and also from recent innovations in the design of specialised vacuum pumping systems. The latest iterations of these special systems will now be described.

[2] Ivasyshyn O.M., Aleksandrov A.V., Fizyko-Khimichna Mekhanika Materialiv Vol.44, No.3, (May-June 2008), pp.7-20

Vacuum arc refining

The vacuum arc refining (VAR) furnace is especially suited to processing reactive metals like titanium (Ti) and has been used for purification of this metal since the 1950s. In simple terms, a long electrode is assembled from purified Ti sponge, scrap and clean recycled Ti metal, and this electrode is then placed in a vacuum chamber above a water-cooled copper mold which is electrically grounded. A DC arc is struck between the two and this melts the end of the Ti electrode, gradually consuming it as molten metal drops into the copper mold and slowly builds up a purified Ti ingot below. The melting process is usually done twice to obtain the desired Ti purity and metallurgical structure, so the first melt ingot is usually re-melted in a second VAR furnace to produce a purer second melt ingot. Melting by electric arc under vacuum in VAR provides many advantages over induction melting techniques, such as the complete elimination of contact with atmospheric air gases, efficient removal of dissolved gases (e.g. hydrogen and nitrogen), removal of lighter metallic impurities, and achieving directional solidification through the resulting purified ingot.

The operating pressure range inside the Ti VAR furnace must be in the region of 1×10^{-2} to 1×10^{-3} mbar or lower, and a substantial vacuum pumping speed must be provided under these conditions to ensure the complete removal of all of the gaseous impurities arising. In addition, the nature of the process creates much fine dust, plus the risk of larger agglomerations or splatter particles, and these can be transported by the gas flow towards the vacuum pumps, particularly during the initial stages of the process. Where significant amounts of raw Ti sponge material are used in the electrode there is also the problem of chloride compound evolution, which can cause significant corrosion issues wherever the exhausted gases contact the atmosphere.

To accommodate these characteristics the classical Ti VAR vacuum pumping system includes vapour boosters as the ideal type of vacuum pump suited to hold very low operating pressures against the high gas loads and high particulate loads. Vapour boosters are a well-established and unique technology, but as “secondary” pumps require to be backed by other vacuum pumps capable of exhausting pumped gases to atmospheric pressure. A typical Ti VAR system is shown in Fig. 1.

The vapour booster pumps are usually connected to the VAR furnace by a large diameter duct (or “plenum”) to minimise vacuum conductance losses at the low process pressure. Behind them are the backing pumps, which are usually a pair of mechanical booster plus dry primary pump combinations. The mechanical booster/dry pump combinations will also have a direct connection to the furnace, and this is used for initial pump down (“roughing”) of the furnace, to reach the pressures at which the vapour boosters can start to operate. This line is provided with a suitable filter unit to capture dust and particles carried along by the evacuated gases. During roughing the vapour boosters are generally isolated by valves and held under vacuum by a small holding pump.

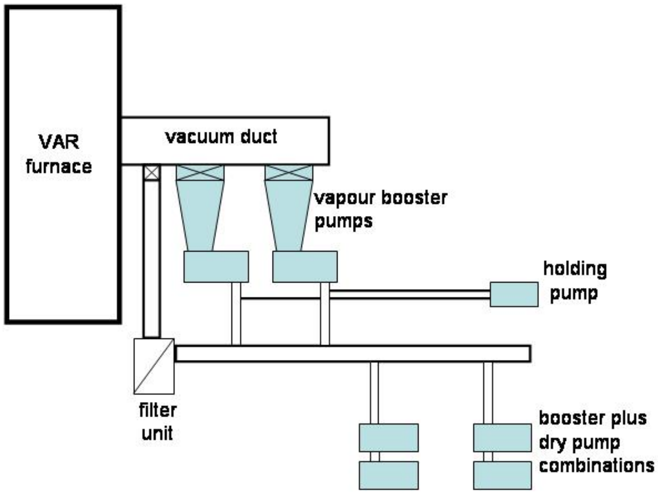

Fig. 1. Schematic of a classical vacuum pumping system for a medium-sized titanium VAR furnace

At the appropriate low pressure the vapour booster inlet valves open, the direct line from the furnace to the backing pumps closes, and the full pumping speed provided by the vapour boosters can be applied directly onto the furnace.

The key advantages of this classic system are that the vapour boosters are a capable and cost-effective means of providing a consistently high pumping speed at very low pressures despite the dust contamination coming from the process, since dust particles are simply absorbed into the vapour booster's oil and sink to the bottom of it's oil boiler tank. Furthermore, the use of dry mechanism primary vacuum pumps in the backing pump combinations provides the advantages of good dust handling, consistent vacuum performance, and low maintenance, compared to traditional oil-sealed ("wet") primary vacuum pumps. Since dry primary pumps are hot-running the risk of corrosion from condensation of chloride residues in the pump exhaust is also substantially reduced. Pumping speed curves for the vapour boosters and backing pump combinations in a typical VAR vacuum pump system are shown in Fig. 2.

Electrode plasma welding systems

One of the key processes associated with the VAR furnace is the assembly of the primary Ti electrode. The electrode composition can be new raw material (i.e. clean Ti sponge), together with appropriate alloying additions, or made from carefully inspected and cleaned Ti scrap and off-cuts (called "revert"). Usually new sponge material is first crushed together into briquettes in a large press and then the briquettes are welded together to form the long electrode assembly.

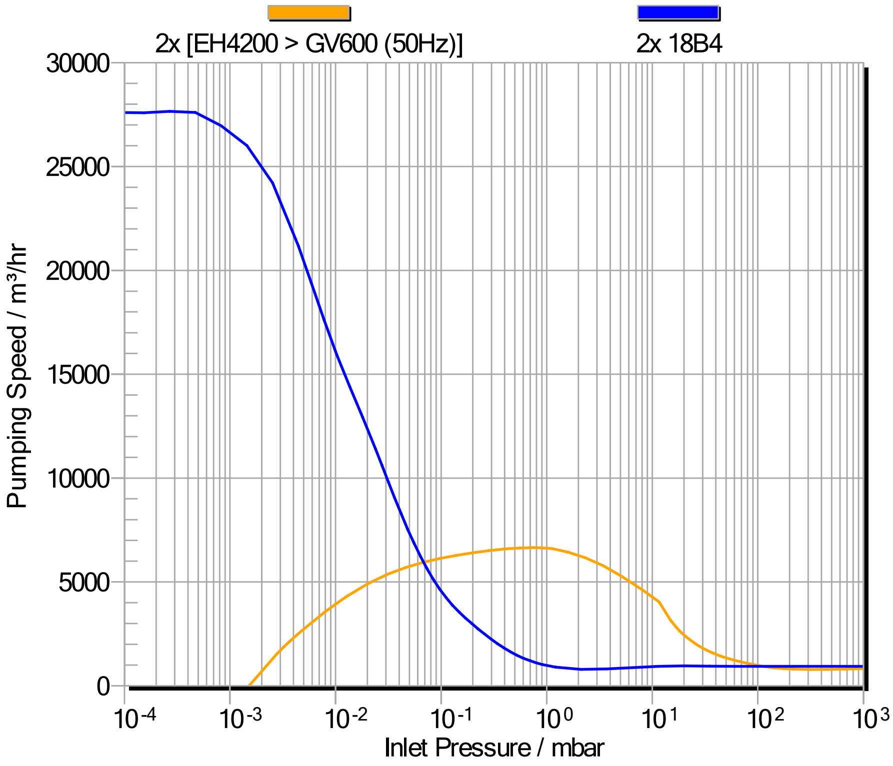

Fig. 2: Pumping speed curve of two 18B4 vapour booster pumps compared to their EH4200>GV600 backing pump sets in a typical VAR vacuum pump system.

Alternatively, many larger revert pieces can be simply welded together into an electrode. Argon plasma welding in a chamber with an inert argon atmosphere is a common method to achieve electrode assembly especially for briquettes, but it is essential to remove all the air from the welding chamber and from the material before starting to weld, to avoid any risk of oxide or nitride formation at the high welding temperatures. For this reason a typical plasma briquette welding furnace is equipped with a vacuum pumping system which provides for both initial evacuation of air and chamber argon pressure control during the process. A typical example is shown in Figs. 3 & 4.

This dry pumping system has two sets of pumps on independent pipe lines, with each set protected by a large filter (F1 and F2 in Fig.3). The filter is a vessel part-filled with dry packing rings (e.g. Raschig or Pall rings), which are ideal for permitting high gas flows while still efficiently trapping the heavy particulate load arising from the plasma welding process. This type of filter is easily cleaned by removal and careful washing of the packing rings.

At the start of the plasma welding process the furnace must first be fully evacuated down to 0.1 mbar to ensure that all atmospheric gases are effectively removed from the furnace and the briquettes.

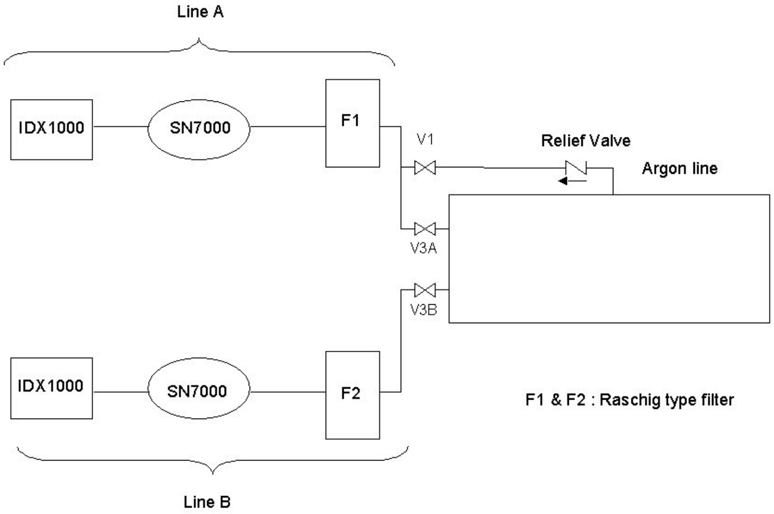

Fig. 3. Schematic of a two-set vacuum pumping system for a large titanium electrode plasma welding chamber

Because of the very high surface area of the briquette material, and consequently the very high outgassing load which results on evacuation, a pumping system is needed with a high pumping speed in the 10 mbar to 0.1 mbar region. This means that two sets of large mechanical booster pump (SN7000) plus large dry primary pump (IDX1000) are used. Both full pump sets are required for the initial evacuation and the pump down usually takes from 30 to 50 minutes. After this, the furnace is re-filled with pure argon to a pressure slightly above atmosphere, to ensure that no air can leak in again. The plasma welding process then takes place and this can last for several hours. During the welding phase only one dry primary pump is left running (IDX1000 in Line A in Fig.3) so that as thermal expansion of the argon atmosphere in the furnace periodically opens the argon line pressure relief valve, the vented argon is safely exhausted by this running pump. Finally, at the completion of the process, this pump alone is used to re-evacuate the furnace to remove the argon atmosphere prior to venting with air.

A particular feature of the pump sets used in this application is the use of high flow gas ballast on the IDX1000 primary pumps, using compressed air. This fulfils two important purposes. Firstly, it provides a constant gas flow through the IDX1000 to keep any residual dust and corrosive particles moving through the pump and out into the exhaust, to keep the pump internals clean. Secondly, because pumping pure argon in a dry mechanism pump at inlet pressures below ~50 mbar can create excessive internal compression heat, dilution of the pumped argon with a constant air gas ballast flow provides a convenient and highly effective method of reducing this heating effect and avoiding any risk of excessive pump operating temperatures.

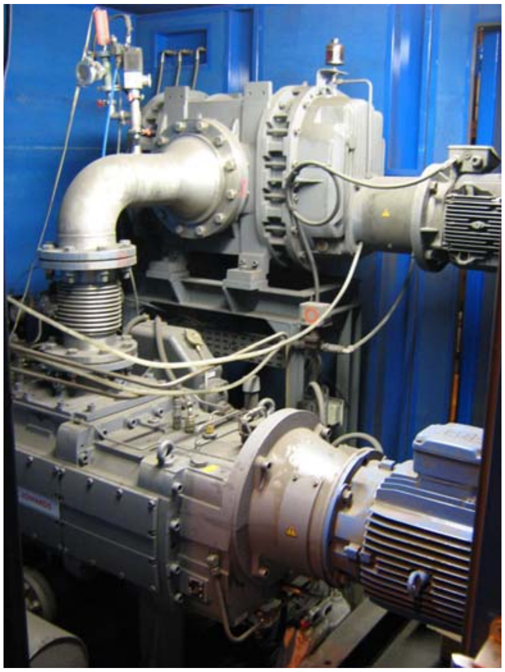

Fig.4. One dry mechanical vacuum pump set for the large titanium electrode plasma welding chamber

Induction skull melting (ISM)

Patented in 1988, the induction skull melting (ISM) process, sometimes alternatively described as vacuum skull (re)melting, offers several advantages particularly for titanium investment casting. It has fast become an attractive, high efficiency process for the lower cost production of high quality titanium castings, able to use Ti scrap, revert and sponge in any proportion, and produce high quality results. ISM uses a vacuum furnace which has a water-cooled, copper crucible inside. But unlike the traditional VAR process, this crucible is made of electrically isolated segments in such a way as to permit an induction field to be generated in the Ti feedstock inside the crucible, without heating the crucible itself. The Ti is melted and circulated by the induction field, forming a molten dome with solidification underneath at its interfaces with the cold crucible – thus creating a solid, outer Ti “skull” containing pure, molten Ti inside, constantly circulating and fully exposed to the vacuum, and not in contact with any other materials. Once melting and purification under vacuum is complete, the pure liquid Ti is promptly cast into the desired mold (located beside it in the vacuum chamber), leaving the solid “skull” behind in the crucible. This skull of purified Ti can then be re-used in the next cycle.

The vacuum levels required for ISM are not quite as demanding as for VAR, but ISM vacuum systems have some special requirements, due to the very high purity of the Ti castings being made, and to both the technological and safety needs of the ISM furnace itself. As a first priority, the potential for large amounts of particles and dust generated especially during the pouring operation, and the possibility of this dust to contain corrosive chloride materials arising from the use of Ti sponge feed stock, means that initial turbulent flow evacuation of the chamber at the start of the process can draw substantial amounts of contamination into the vacuum pumping system, as the chamber pressure initially falls from atmospheric pressure down to around 200 mbar. For this reason it is usual to first evacuate the chamber down to 200 mbar using a separate, auxiliary liquid ring pump (LRP) system, since LRPs are particularly suited to operating down to this “rough vacuum” pressure and are very tolerant to large amounts of particulate contamination.

However, to achieve the required deep vacuum for operating the ISM process (typically down to below 0.05 mbar) and especially to avoid any risks of furnace contamination by back-streaming of pump fluids at these low pressures, only dry mechanism pumping systems can be considered for the main vacuum pumping system.

The overall system pumping capacity must be sufficient to hold the highest theoretical gas loads from the process to within the acceptable chamber maximum pressure – for a typical ISM furnace this means holding a pressure of less than 0.1 mbar at maximum system gas flow rate. This requires a three-stage pumping solution and is a particular challenge when the required pumping capacity is specified in terms of hydrogen (H_2, which is a common contaminant of metals) since dry mechanism primary pumps in particular can have a low pumping efficiency with hydrogen unless special precautions are observed.

To maintain chamber cleanliness, special argon purges to the mechanical booster pumps are required to avoid any risk of booster gear box oil emissions or air ingress contaminating the process. The risk from chloride process contaminants means that the mechanical booster exhaust gas after coolers must also be operated at elevated temperatures, so that they do not create cold spots in the gas path which might cause condensation and corrosion, and the primary dry pumps must be adequately purged in operation to avoid any risk of corrosion. The generation of much fine dust from the process requires that adequate filtration of the pumped gases, plus appropriate dust cleaning facilities, are installed in the vacuum pumping system. The primary pump shaft seal and gas ballast purges are also supplied with argon, instead of compressed air, to eliminate any risks from corrosion or from possible hydrogen content of the pumped gases. These purges are also required to significantly enhance the primary pump’s hydrogen pumping capacity, in case hydrogen is present.

In the most recent state-of-the-art ISM installations, flexible vacuum pumping systems are employed which can be switched between various ISM and even VAR furnaces depending on production demand. An example of such a flexible three-stage vacuum system, using two stages of mechanical booster pumps backed by dry claw mechanism primary pumps, is shown in Figs. 5 & 6. This provides vacuum for a plant having one large ISM furnace, together with one smaller ISM and a small VAR. The system is sized to provide the required vacuum pumping capacity for the large ISM when all pumps are used together. However, it can also be operated as two independent pumping skids (in Fig. 5 labelled Skid A and Skid B, by closure of valves V1 and V2) so that the smaller ISM and the VAR can both be operated simultaneously if production demands require this.

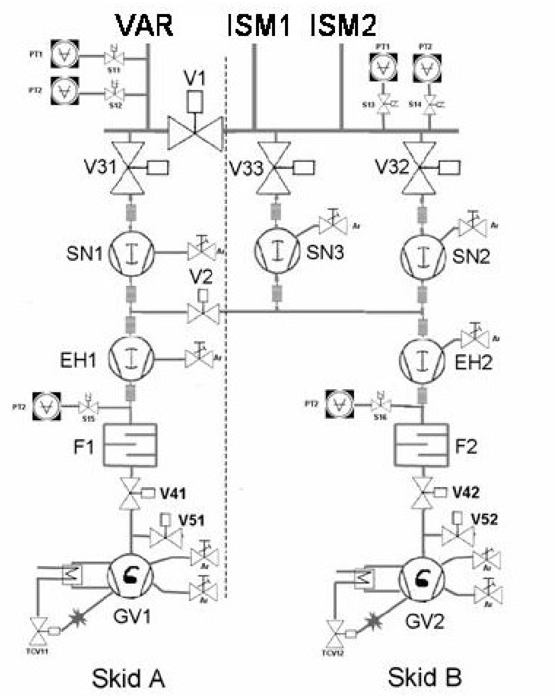

Fig. 5. Schematic of a two-part dry mechanical vacuum pump system for a multi-chamber titanium refining plant including two ISM furnaces

Recent live test results on this system with all pumps running together confirm that an effective hydrogen pumping speed of over 25,000 m^3/h H_2 at 0.1 mbar is achieved with this design, which is very close to the theoretically-predicted H_2 pumping speed value from computer modelling of this pumping system.

Other significant features of this special system include the provision of large dust filters in the gas stream in front of the primary dry pumps (Fig.5 labelled F1 & F2, in front of GV1 & GV2), This location for filtration to protect the primary pumps is ideal since gas pressures are comparatively high here, meaning that pumping speed losses through the filters are minimal, and any dust tends to pass easily through the two stages of mechanical boosters preceding the filters anyway. To avoid long term residual dust accumulation there is also a shut down air purge cleaning system fitted to primary pumps GV1 and GV2, which admits atmospheric pressure air through valves V51 & V52 and through the primary pumps for a few minutes prior to shutting them down at the end of the process.

Fig. 6. Two-part dry mechanical vacuum pump system manufactured for a multi-chamber titanium refining plant including two ISM furnaces

Primary vacuum pumping technology

The “primary” vacuum pump of any vacuum system is the pump which finally exhausts the pumped gases to atmospheric pressure, and by definition this must be a mechanism with a very high gas compression. As noted above, in Ti refining processes large amounts of residual dust can be carried along by the effluent gases to the vacuum pumps, and so it is important to ensure that each pump system has adequate dust filtration installed to minimise the dust load, especially on the primary pumps. Dust contamination problems are much worse if a dry mechanism primary vacuum pump is not used, because any oil-wetted vacuum primary pump mechanism will suffer significant contamination of its sealing oil and continuous degradation of its pumping performance on these metallurgical processes. For this reason the best choice of primary pump for Ti refining systems is a very robust, dry clearance vacuum pump, such as the dry claw or dry screw type, as both these types have internal gas flows at high temperature and high turbulence. These conditions provide the dry pump with excellent resistance to metallurgical dust contamination, wear, and the effects of corrosive chloride contaminants arising especially from Ti sponge material. Typical examples of large dry screw vacuum pumps, with extensive experience on metallurgical applications are the IDX1000 and IDX1300. These are the latest generation of large, dry, double-ended, variable pitch screw pumps, with high pumping speeds (nominally 1000 m^3/h and 1300 m^3/h respectively), good ultimate vacuum capability, excellent resistance to dust contamination, and which are qualified for pumping both argon and hydrogen gases from Ti processes. The IDX1000 is illustrated in Fig.7.

Fig. 7. Large (1000 m^3/h) double-ended dry screw vacuum pump for metallurgy applications, type IDX1000

Summary

The use of the latest dry vacuum pumping technology, together with extensive practical vacuum system experience on Ti refining processes, now enables more reliable and more cost-effective vacuum pumping solutions to be applied to modern Ti refining plant. This can provide the owner with more efficient and flexible plant operation, which can then lead to a more competitive supply of Ti materials. It is considered that such improvements in technology can ultimately provide enhanced opportunities for further diversification of the applications of this important metal.