Inductive melting in cold wall crucible: technology and applications

by **Hans Windsheimer, Roland Waitz, Peter Wübben**

This article describes the current developments in the area of inductive cold wall crucible melting. Recent applications regarding melting of reactive metal alloys as well as the corresponding equipment at Linn High Therm (LHT) for laboratory as well as semi-industrial cold wall crucible melting furnaces are presented.

Reactive and high melting metals, e.g. titanium, tantalum, niobium, molybdenum, cannot be molten in ceramic or graphite crucibles in high purity grades. Chemical reactions with crucible materials result in melting impurities which, in turn, lead to characteristic degradations of the metals during later use. Melting of titanium and titanium alloys in oxide ceramic crucibles, for example, leads to oxygen absorption in titanium which results in embrittling effects [1]. These undesired impurities can, in many cases, only be prevented by using the so-called cold wall induction crucible technology. It is an induction heated water cooled copper crucible which contains the metal melt (**Fig. 1**). Due to the contact between metal melt and crucible, heat is released from the melt which results in a thin layer of solidified metals as barrier between crucible and melt. This layer prevents direct contact between melt and crucible and thus prevents chemical reactions respectively diffusion of impurity elements. Thus high purity and high melting metals can be treated successfully [2].

Cold wall crucible melting represents a special kind of heating of electrically conductive materials by alternating electrical fields. Due to Ampère's law, current flow leads through an induction coil for creating a magnetic alternating field, which, in turn, leads to an electric conductor – here: cold wall crucible made of copper – inside the coil for creation of alternating current.

The easiest design of a cold wall crucible consists of a ring-shaped wall of single, water-cooled palisades which are fixed on a bottom plate. The water-cooled palisades made of copper do not have electrical contact between each other. Due to the flow of induced currents inside the palisades, the single magnetic fields total each other which, in turn, create a magnetic alternating field affecting the material and generating heat in the material due to ohmic losses. The solid metal layer (‚skull') between melt and crucible thus acts as self-created insulation layer [3].

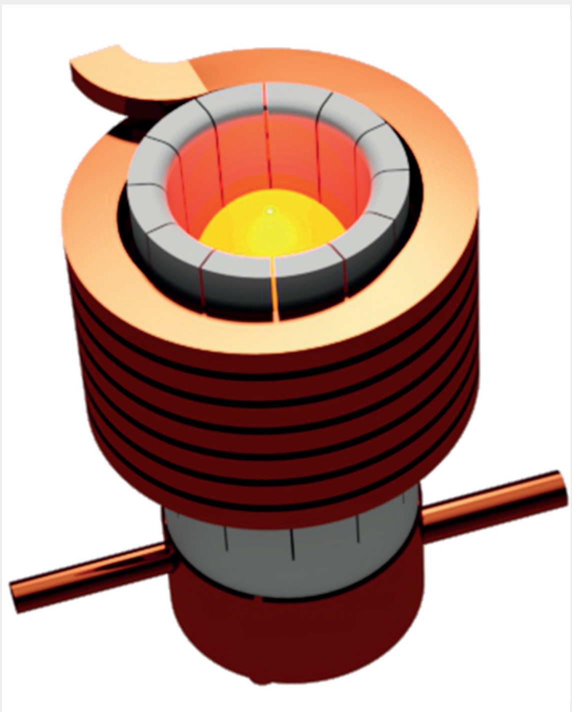

Fig. 1: Schematic display of a cold wall induction crucible with melt

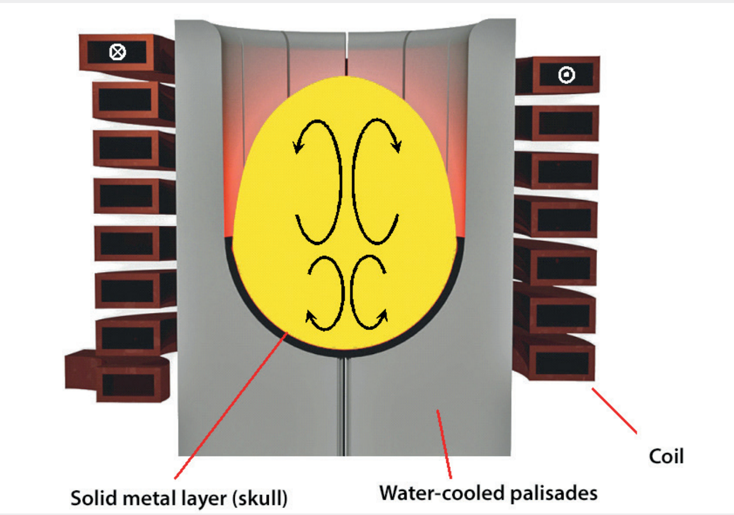

Fig. 2: Sectional view of a cold wall induction crucible (CWC)

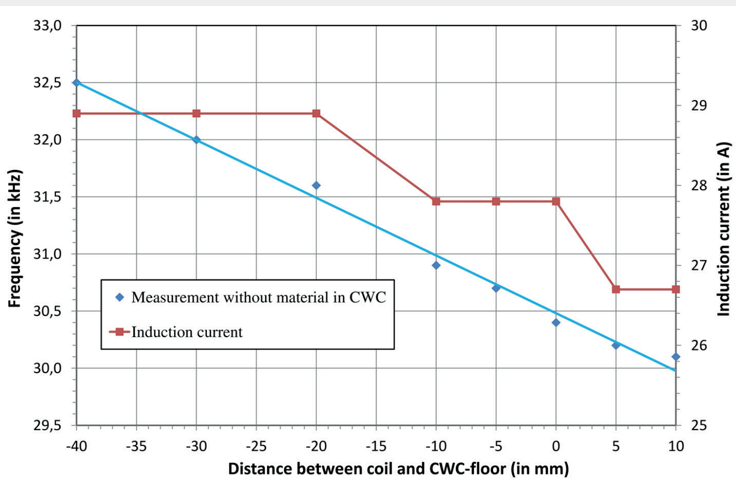

Fig. 3: Variations of coil position

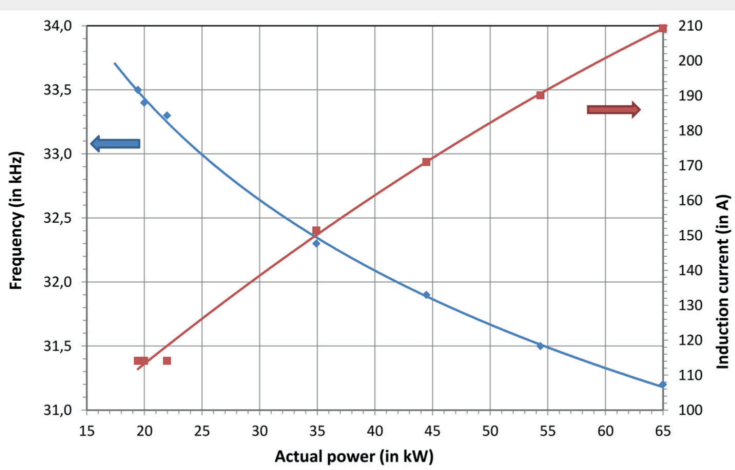

Fig. 4: Typical variation of frequency and current for filled cold wall induction crucible (V = 600 cm^3)

Fig. 2 shows a schematic drawing of a cold wall crucible as well as the corresponding induction coil for melting metals. Sufficiently high applied power respectively high magnetic fields around the palisades lead to a so-called melt cap due to the involved electromagnetic Lorentzian Forces, i.e. the metal melt is mostly not in direct physical contact with the crucible palisades. This has a benefit on the melting behavior for attaining of high material purities and decreased heat losses.

APPLICATIONS

Despite comparatively high energy consumption together with low energy efficiency, melting in a cold wall induction crucible (CWC) becomes more and more popular. Due to temperatures of considerably more than 3,000 °C, refractory metals and their alloys, which are highly aggressive in liquid state, can be molten nearly contamination-free. As there cannot arise any contamination by crucible materials and melt can be overheated nearly arbitrarily, this technology can also be used for vaporization of contaminations in high purity materials e.g. in semiconductor industry.

Generally, the cold wall crucible technology has established itself in the processing of titanium and titanium alloys and is used wide-spread [4, 5].

Apart from that, melting in a cold wall crucible furnace is one of the most promising technologies for remelting and vitrifying of nuclear waste [6-8]. As there is no contamination caused by crucible materials and as the cold wall crucible can be used repeatedly, only very small quantities of contaminated materials accumulate as final repository waste.

Melting in a cold wall induction crucible is especially suitable for materials whose electrical conductivity increases considerably with temperature, e.g. glasses and ZrO_2 [9, 10]. The initial material which is electrically insulating at ambient temperature has to be put into the cold wall crucible in powder form. It has to be pre-heated until it reaches sufficient electrical conductivity with increasing temperature. Thus a material which can be heated easily by induction at room temperature has to be added as susceptor into the crucible. In case of ZrO_2, this can be realized by a piece of metallic zirconium or in case of glass by a piece of graphite. In both cases, the powder is heated up by thermal conduction in direct ambient of the susceptor until it has enough conductivity for being directly heated inductively. Depending on the material, this temperature range is between 600 and 1,200 °C. The initial material oxidizes at high temperatures and air atmosphere like zirconium to ZrO_2 or graphite to CO_2, which does not leave any marks in the material as gas. If there is nevertheless danger of contamination, the "initial material" can also be "packed" in quartz and can be removed from the crucible after pre-heating.

As electrical conductivities of oxide materials are generally low, a sufficiently deep penetration can only be attained by increasing the necessary working frequency into the MHz range [10].

Nowadays, ZrO_2 produced in such way is the quantitatively most important monocrystalline material after silicon and sapphire. Due to its high index of refraction and its high brilliance, it is used as gemstone (= artificial diamond).

DESIGN OF COLD WALL CRUCIBLES

Laboratory furnaces with cold wall induction crucibles with a melting volume of 2-20 ml (corresponding to 16-160 g stainless steel) can be easily obtained commercially. Moreover, furnaces for melting quantities of higher kg ranges (cold wall induction crucible volume 30 dm³ correspond to 240 kg stainless steel) are available on the market.

As manufacturer of electrically heated furnaces, LHT has long experience in manufacturing of induction melting furnaces. Laboratory furnaces for melting in cold wall crucibles already belong to our product range. After intensive development work, LHT successfully closed a gap with cold wall induction crucibles in the range of 0.1-1 dm³ as it is needed for developments in pilot scale manufacturing.

For cold wall induction crucibles of this size, a new development was necessary as they have to be designed completely different than huge production cold wall induction crucibles. Significant for the design is the surface of the crucibles of which more than 90 % of the inserted energy has to be led away. Generally, this is effected by the internal water cooling of the cold wall induction crucible. The flow rate of the cooling water depends on cooling water pressure in the palisades and has to be observed. The corresponding power and current cross sections have to be such that turbulences and dead spots are avoided as they lead to unnecessary pressure losses and an insufficient flow and thus affect the heat outlet.

The energy created by the induction coil cannot be varied continuously like in conventional crucible melting as a certain minimum energy for the magnetic field in the cold wall induction crucible and the consequently resulting electromagnetic power is necessary. The electromagnetic power is decisive for avoiding contact between liquid melt and the side wall of the cold wall induction crucible. The magnetic field which develops in the crucible depends on the position of the induction coil over the bottom of the crucible. In case of the described sizes and designs, the optimum position of the coil was determined by extensive tests. **Fig. 3** shows results with an empty cold wall induction crucible in order to exclude interactions with the sample.

	KIT Laboratory unit	MFG 100 Multi-crucible unit	MFG 180
P_{max} (kW)	10	2 x 50	180
Power input (kVA)	14	130	230
Atmosphere	Vacuum (10^{-2} mbar), Ar	Vacuum (10^{-5} mbar), Ar	Vacuum (10^{-5} mbar), Ar
T_{max} (°C)	2000	1800-2000	1800-2000
Frequency (kHz)	150 - 450	40-50	30-40
Crucible volume (cm³)	25	100 - 300	800 – 900
Application	Non-ferrous and refractory metals	Pure Fe materials	Stainless steels, Ni-base alloys

Fig. 5: Overview of selected cold wall crucible induction furnaces as well as their basic data and melting objects

From the diagram one can see that in case of a coil position significantly above the bottom of the cold wall induction crucible, the inlet current to the induction coil is lowest, as coupling is insufficient. In case of a coil position deep under the bottom of the cold wall crucible, there is a constant higher current. The optimum position of the coil is the plateau between both extremes. There is a balance between maximum coupling of the cold wall crucible and the design related short circuit current in the cold wall induction crucible underneath the crucible bottom.

Fig. 4 qualitatively shows the current and frequency flow resulting from optimum coil position depending on the applied actual power. The indicated diagrams help to determine the optimum operation conditions customized to the application purposes.

LHT-COLD WALL INDUCTION FURNACES

Depending on the application, cold wall crucibles as well as the corresponding induction furnaces can be realized in a multitude of sizes. For melting trials in laboratory scale, mostly only small crucible volumes of only a few cm³ are sufficient. However, the frequency range has to be as wide as possible due to possible material variability and the subsequent wide range of necessary working frequency.

For laboratory trials as well as prototype production, crucible sizes from 25 to 1,000 cm³ are suitable. **Fig. 5** gives an overview of various cold wall crucible furnace, the respective crucible and coil designs as well as typical melting samples. For decreasing the average melting time resp.

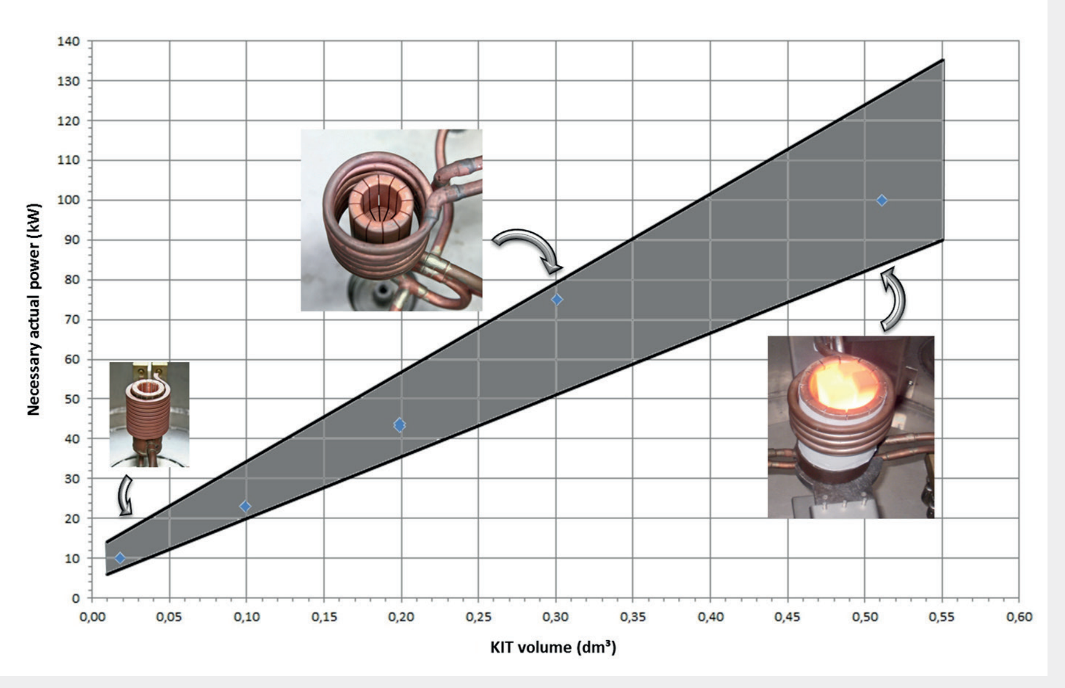

Fig. 6: Range of applied actual power of various cold wall induction crucibles depending on crucible volume

for increasing the throughput, such furnaces can also be equipped with several independent operative coil-/crucible systems. A wide range of crucible and coil characteristics enables melting of various materials, e.g. stainless steel resp. titanium or titanium alloys. These furnaces can be adapted to customer's requirements with a number of options, such as gas-feeding device, pyrometer or vacuum pump stands.

From intensive test campaigns with a number of various furnaces and cold wall induction crucibles results a range of necessary applicable performances depending on the crucible volume, **Fig. 6**. Some of the used crucibles in the volume range of 25 to 500 cm^3 are shown exemplarily. The fluctuation range results from the influence of various melting materials and thus related different process temperatures.

CONCLUSION

The realization of cold wall induction crucibles in laboratory and/or production scale requires an adaption to the respective requirements regarding charge size and composition of the material to be molten. Depending on specification, mostly various conceptions are necessary, e.g. in order to guarantee sufficient cooling of the crucible and in order to be able to use the electric currents induced in the cold wall induction crucible for a complete and stable magnetic field.

LHT realized this in an extensive development program and thus adapted its program range regarding melting in cold wall induction crucible in pilot scale, starting from crucible sizes of 25 cm^3 up to semi industrial prototype furnaces with capacities up to 1,000 cm^3. That way LHT can respond to the demands of a broad range of materials, e.g. steels, stainless steels, non-ferrous or refractory metals.

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