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Electromagnetic suspension in induction furnaces

Reduce contamination by minimizing contact between molten metal and the furnace crucible

Executive summary

An induction furnace is an electrical furnace in which the heat is applied by induction heating of metal. This is a clean, energy-efficient and well-controlled melting process compared to most other means of metal melting. Induction furnaces with cold crucibles (CCIF) are widely used for the melting of super-pure metals and alloys as they reduce load contamination compared to traditional furnaces with a ceramic crucible. This is due to the water-cooling system.

However, in some applications, a small but unacceptable level of contamination occurs when molten metal contacts cold copper. A higher level of purity requires fully eliminating molten metal contact with cold crucible walls during the melting process.

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Abstract

The goal of reaching a higher level of purity can be achieved by holding molten metal in suspensive condition during the melting process. Practically, the electromagnetic (EM) field of the coils in this furnace must not only create the heat for induction melting, but also provide EM suspension of melted metal.

Each induction melting furnace creates some meniscus of molten metal in the process of melting.

As a rule, the meniscus volume is small and does not have any influence on the melting process. In full suspension, the molten meniscus volume must be commensurate with the full load volume of the furnace; ideally, 100 percent of it. Creating such furnaces requires developing a calculation method that must take into consideration a combination of closely bound electromagnetic, thermal, hydrostatic and electrodynamic processes. The objective of this white paper is to describe such a calculation method.

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Providing an example

We will describe this developed method with a tangible example:

- Load: material is titanium, solid load diameter is 76 millimeters (mm), initial load height is 100 mm, temperatures (initially 20 degrees Celsius, melting is -1,660, overheating is -1,800), latent heat fusion is 419 kilo-joules per kilogram (kJ/kg)
- Cold crucible: material is copper, minimum initial diameters are from 80 to 140 mm, height is 273 mm, number of sections are 12 and 24, gaps between sections are 0.5 mm
- Induction coil (combination of cylindrical and conical groups of turns): material is copper, minimum inner diameter is 166 mm, height is 160 mm
- Electrical parameters: frequency is 10,000 hertz (Hz), nominal inverter power is 100 kilowatts (kW), upper limit of coil voltage is 1,000 volts, upper limit of coil current amps

Let's recall how the cold crucible furnace works. Figure 2 shows an example of magnetic field distribution in an induction furnace with cold crucible. Magnetic flux created by an induction coil can be conditionally divided into three parts:

- Coil flux leakage
- Flux along the crucible's sections
- Flux that passes to the load through crucible sections

The ratios between the three parts of magnetic flow determine the efficiency of the furnace. The more that is part of load magnetic flow, the higher the efficiency. The number of sections has a strong influence on the cold crucible as well as on all the furnace parameters. Comparing simulation results between crucibles with 12 and 24 sections shows useful magnetic flux and the electrical efficiency of the furnace with the 24-section crucible is significantly higher than in the furnace with the 12-section crucible. The additional advantage of the 24-section crucible is due to a more uniform distribution of the magnetic field along the load azimuth perimeter. This significantly improves stability of the molten load meniscus.

Figure 3 shows the distribution of currents induced by furnace coil in two variants: solid and a combination of solid/molten loads.

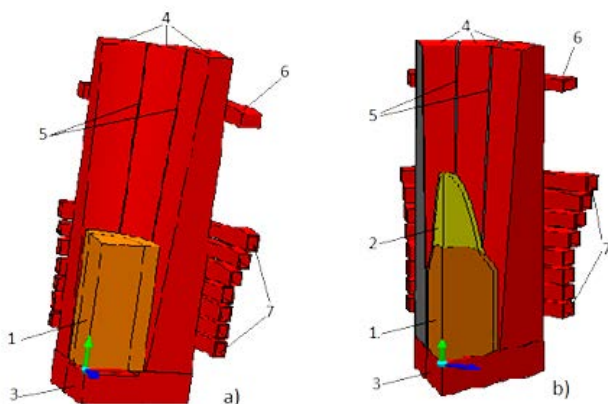


Figure 1: 3D models of furnaces with cold crucible. a) solid load, 12-section crucible, 1/4 of furnace; b) partially molten load, 24-section crucible, 1/8 of furnace; solid load, 2-molten load, 3-crucible bottom plate, 4-crucible sections, 5-gaps between sections, 6-flux ring, 7-induction coil. Note: water cooling system of cold crucibles is not shown.

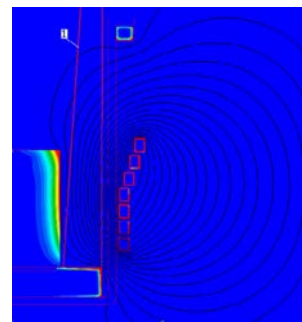


Figure 2.

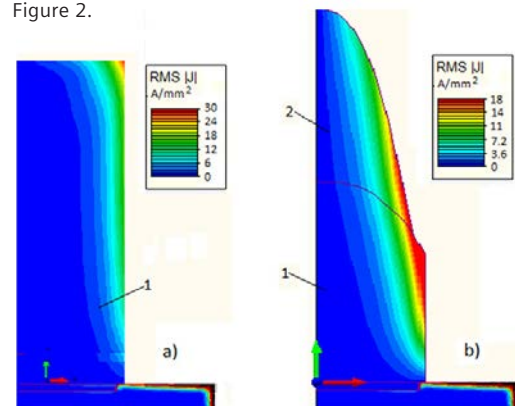


Figure 3.

Facilitating complex calculations

The furnace magnetic field induces current, and therefore heating in both the solid and molten load. At the same time, there are big differences between the two kinds of loads: drastically different shape and material properties. In the process of one furnace heat, during load transfer from a solid billet to molt meniscus, there are fundamental changes to the furnace load parameters. As stated, the furnace must simultaneously melt the load and suspend the molten metal.

The satisfaction of both conditions requires complex calculations. Figure 4 shows the workflow diagram developed for the calculations.

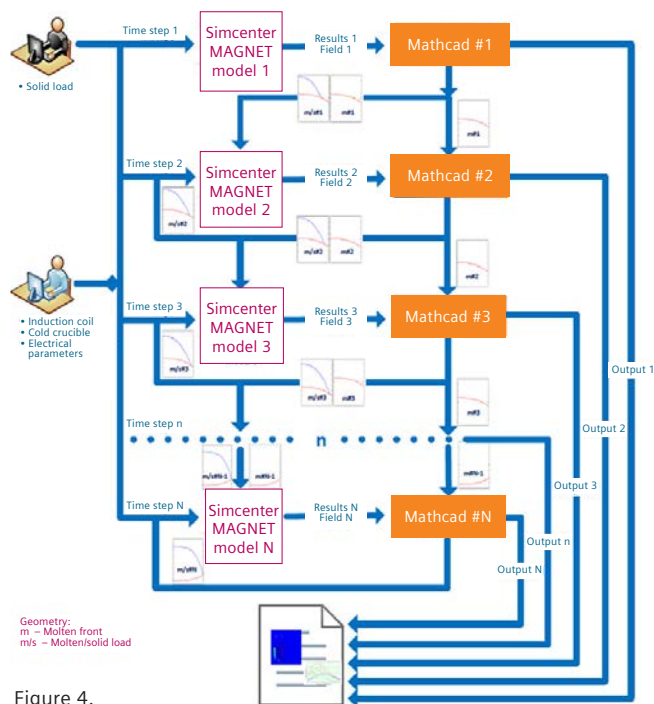


Figure 4.

The total time for the melt, starting from the activation of the furnace to the metal casting, must be divided into time steps. Each time step consists of an independent electromagnetic block made using Simcenter™ MAGNET™ software. The postprocessing of all simulation data is done using Mathcad software. The input in the Simcenter MAGNET model comes from the output

of the previous step. The Simcenter MAGNET models make electromagnetic calculations and transfer the results to the Mathcad program. The Mathcad program uses the results for thermal, hydrostatic and electrodynamic calculations. The results are transferred as input to the next step of the workflow and a common workflow output.

The first step is the time between the start of the heating process and the melting of the top surface of the load. It differs from other time steps because it requires a separate solid load calculation method. The rest is calculated by dividing the remaining time by the number of time steps without the first. Considering the shape of the cold crucible segments requires using Simcenter MAGNET to perform full 3D simulations of the electromagnetic fields. An example of cold crucible meshing is shown in figure 5.

After each step, the results of the Simcenter MAGNET simulation are transferred to Mathcad postprocessing blocks. The blocks support the following operations:

- Calculation of temperature and energy in both the solid and molten parts of the load
- Determination of load meniscus shape
- Meniscus EM stabilization

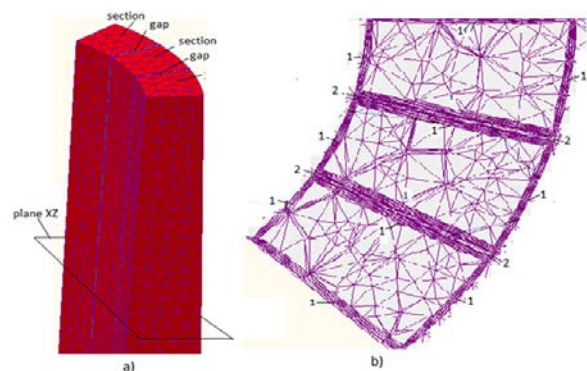


Figure 5.

Taking an iterative approach

The results of each time step are integral parameters and the shape of the molten load. The results are transferred to the next time step input.

Figure 6 is the result of thermal analysis, showing the variation of load temperatures (T) with time.

The graph fixes the molten load front location, which gives the necessary data for load meniscus calculations: Figure 7 shows the meniscus calculation. The calculation of the shape of the load meniscus requires an iterative approach, so the meniscus data is passing, as feedback, into its own Simcenter MAGNET model. Nominally, the load meniscus calculation determines a molten load shape with hydraulic pressure that is equal to the electromagnetic pressure of the coil magnetic field.

The third profile is an ellipsoid of second order with a bottom diameter equal to the solid load diameter and volume of the molten load. The Simcenter MAGNET block has the distribution of the magnetic field in the zone of the molten load, particularly within the outer diameter. The intensity of the magnetic field in this zone can be used to determine the initial meniscus height and its bottom diameter (figure 7, curve 2).

Curve 2 in figure 8 is incompatible with the electromagnetic pressure curve that Simcenter MAGNET produces (See figure 8a). The two curves coincide on its ends, but not in the middle. There are two ways to improve the compatibility of the curves: a) induction coil design and b) induction coil location.

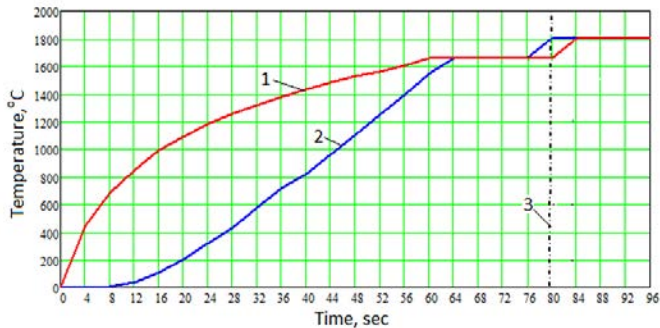


Figure 6.

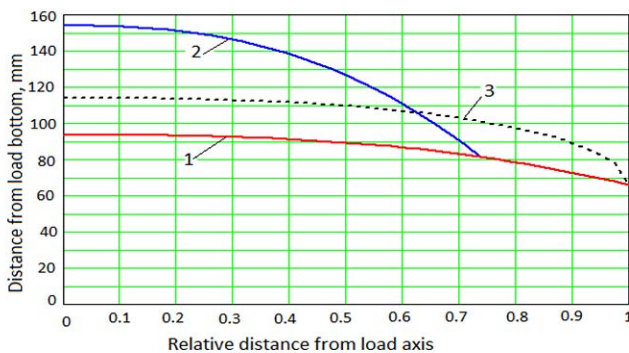


Figure 7.

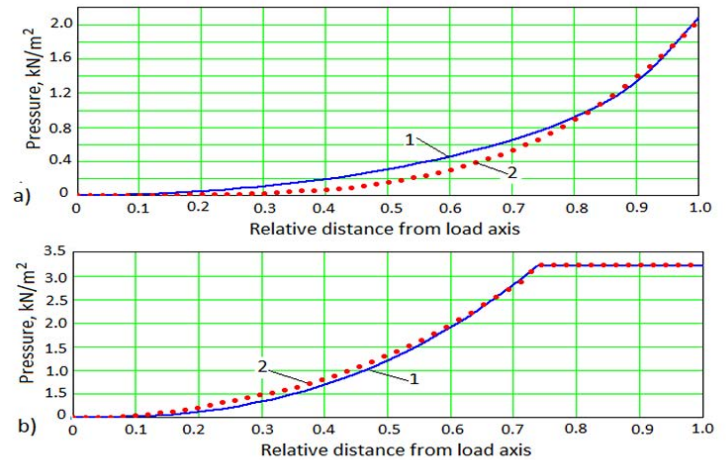


Figure 8.

The coil design method was used from the beginning: this design uses a combination of cylindrical and conical coil turns. This design showed satisfactory results in the initial stages. The curves on the figure 8b show good agreement.

The coil location produced conflicting results: it is impossible to find one optimal location of coil for all variants. The design decision was made to move the induction coil in the process from the top of the furnace heat to the bottom.

The change can be done synchronously with time steps or continually. This variant was explored and showed

satisfactory results. Some examples of the load profile calculations are shown in figure 9.

The developed method efficiency can be defined by estimating the load level utilization of the furnace. The load utilization (LU) coefficient may be used for the goal. The LU coefficient is defined as a ratio between the mass of molten load output and mass of the furnace charge. As figure 10 shows, the LU coefficient is more than 90 percent when the movable induction coil is being used.

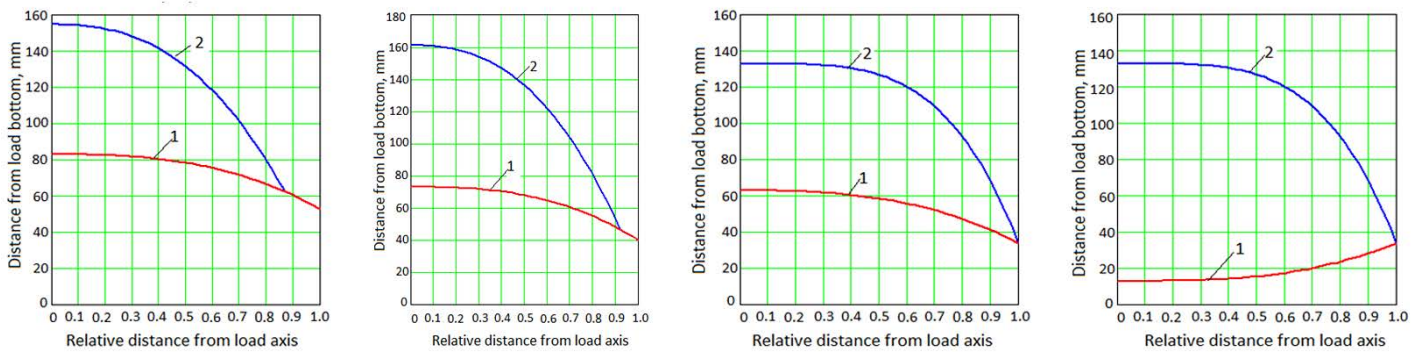


Figure 9.

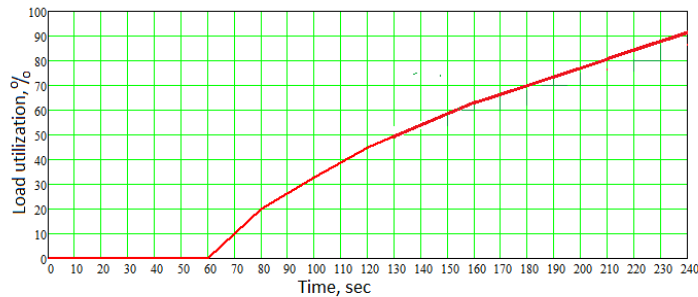


Figure 10.

Conclusion

Using induction furnaces with the cold crucible calculation facilitates the design of furnaces with minimal contact between the molten metal and the furnace crucible. As a result, this dramatically reduces the contamination of the load.

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