The role of the bath movement in recycling scrap using coreless induction furnaces

by Wilfried Schmitz, Alejandro Hauck

One unique and well-known feature of the coreless induction furnace is its pronounced metal bath movement, caused by the electromagnetic forces present. This bath movement, basically depending on the furnace power and operating frequency, is the reason for the good homogeneity of the melt regarding composition and temperature delivered by such furnace type. On the other hand, this feature is widely used for stirring fine sized metallic scrap into the melt. This type of operation can be further optimized and tailored to the specific requirements by employing some new special circuits. Finally, a new technology is presented, allowing to operate a coreless induction furnace at continuously adjustable frequency down to 30 Hz and with adjustable phase shift between two coil sections, thus offering unmatched freedom in selecting heating power and bath movement characteristics independently.

Induction melting has become an increasingly widespread process in the foundry and semi-finished products industries given its technical and economic performance potential. Its basic advantages derive from the direct input of heat into the metal with almost no temperature overshoot and from the fact that the bath movement can be selectively controlled. These properties provide an accurate temperature and process control capability, low melting loss, reduced environmental and workplace pollution, and highly stable and precise analyses, all with high energy efficiency. The step to digitally controlled medium-frequency furnaces based on advanced frequency converter systems has brought a significant increase in power density and process engineering capabilities.

THE CORELESS MEDIUM-FREQUENCY INDUCTION FURNACE

Design and operation
An advanced high-power induction melting system as shown in Fig. 1 is essentially made up of:

- the melting unit with furnace body and cradle
- the electric power supply system with transformer, frequency converter and capacitor rack
- the process control system with weighing system, operator cabinet and melt processor
- the peripheral equipment including water recooler, charger and dust collection system.

State-of-the-art furnaces with advanced frequency converter systems can be operated with a selectable frequency usually in the range between 60 and 1,000 Hz. In new
coreless furnace projects, they have completely supplanted mains-frequency installations due to their numerous advantages.

One major benefit, thanks to the higher frequency, is that the furnace can be started on solid charge material without any losses and it can be reliably operated with a power density which is a multiple of that of mains-frequency furnaces.

One key feature of the coreless induction furnace, distinguishing it fundamentally from all other melting sources, is the movement of the metal bath created by electromagnetic forces. This is illustrated in some detail in Fig. 2, which depicts the current-carrying water-cooled induction coil and symbolically indicates the direction of the current flow. It also shows the refractory crucible which contains the melt and is arranged inside the coil. The inductor current produces a magnetic field which in turn induces ring currents in the molten metal. It should be noted here that the current density is highest, due to the skin effect, in the rim zone of the melt directly adjoining the crucible wall. Because the currents are short-circuited, Joulean heat is generated in the melt. In addition, these currents – extending in a direction opposed to that of the inductor current – produce a secondary magnetic field. Due to this effect, the coil exerts repelling forces on the melt. With a coil of infinite length, the magnitude of these forces would be the same at all places over the coil height. In a finite coil as encountered in practice, the electromagnetic force density is variable over the height of the coil (Fig. 2). Hence, melt volumes situated at the centre of the coil encounter a more intense repelling force and hence, are accelerated more strongly in the direction of the coil axis than melt regions located near the edge of the coil.

One consequence of this situation is that a flow pattern resembling two rotational toroids will form in the melt. In a high-power furnace, the local flow velocity may amount to as much as 1–2 m/s. Moreover, a so-called bath meniscus will form at the surface of the melt due to the equilibrium between the repelling electromagnetic force and the force resulting from the metallostatic pressure.

The intensity of this bath movement firstly depends on the furnace power; the higher the power input, the more vigorous the bath movement will be. But the flow intensity also depends on the frequency of the alternating current fed to the coil. The lower this frequency, the stronger the bath movement. This implies first of all that for a given fixed frequency, the heat input into the melt and the intensity of the bath movement are always correlated. Moreover, for a given specified furnace power, the intensity of the bath movement can be selectively controlled by choosing a suitable operating frequency.

Ultimately, for a given power and frequency, the intensity of the bath movement varies with the furnace bath level. This is particularly true for the metal flow at the melt surface.

In the above considerations we have assumed laminar flow conditions for reasons of descriptive simplicity. In reality, however, a substantial turbulent flow portion will be superimposed over the laminar flow. This will be more pronounced the lower the furnace’s operating frequency is.

This bath movement is very important from a technological viewpoint since it facilitates an optimum melt homogenization and stir-down of constituents, thereby ensuring an optimum melt composition with excellent analysis and temperature accuracy at the same time.

As described in detail, the bath movement intensifies with rising electrical power input but diminishes as the frequency is raised. And again, for a given furnace power level, the heat input and intensity of the bath movement are interlinked. Therefore, a classic mains-frequency three-phase stirring circuit used to be (and still is) employed in situations where a strong stirring action is required at minimized heat input. However, this approach is associated with high costs. Modern converter technology now provides alternative solutions to this task which are described in the following sections.

Special circuitry

From a metallurgical point of view, the ideal induction melting process is one in which both the input of thermal power and the melt flow can be controlled to match given technological needs. In addition, the power input and bath movement should be mutually decoupled, i.e. the desired melt movement in the furnace should be adjust-
able independently of the respective power input. While it is no problem technologically to control the electric power and hence, the input of thermal energy into the melt, it takes very special circuit engineering to achieve control of the bath movement independently of this energy input.

Moreover, when discussing intense bath movement, it is necessary to distinguish between deep intermixing of the entire melt and mere surface flows, as shall be explained later.

Based on R&D advances achieved over the last few years, Otto Junker has established its Power-Focus and Multi-frequency technologies – two special circuit systems meeting the above requirements which have by now proven their merits in numerous installed furnace systems.

The Power-Focus technology permits an automatic or freely selectable concentration of power in that coil section (top or bottom) in which it is needed most. Thus, when the furnace is half empty, the power input can be focused in the lower crucible area in order to increase the energy input there. On the other hand, when the furnace is full one can direct more power into the top coil section so as to intensify the bath movement and hence, facilitate stir-down of the charge (e.g. metal chips or fines).

The Multi-frequency technology enables switching between different operating frequencies during the melting process. For example, an appropriate frequency of 250 Hz will be used to melt down the charge material. For the input of carburizing agents and/or alloying additives, the system is automatically switched to a lower frequency, e.g. 125 Hz. Practice has shown that this changeover to a reduced frequency can greatly accelerate the carbon pick-up in for example cast iron analysis adjustment (Fig. 3).

It should also be mentioned that these two circuit configurations can be combined to amplify their respective effects. These options are substantially expanded further by the latest developments utilizing the technical advantages of IGBT converter technology.

Apart from proven thyristor-based frequency converters, the successful development of special IGBT converters has come to play an increasingly important role in electrother-
mal processes. These systems involve the use of insulated gate bipolar transistors (IGBTs) instead of thyristors in the inverter.

The inverters and d.c. link circuit capacitors form one integral unit. This unit is suitable for use in a variety of circuit configurations. Typical examples are:
- Independent inverters serving several furnaces
- Multiple inverters for the coil sections of one furnace
- Parallel connection for increased power
- Series connection for increased voltage.

Recent engineering advances have yielded IGBT converter systems, whose process technology applications are to be explained on the basis of appropriate examples [1].

The technical prerequisites for controlling the bath movement within a wide range are met by installing an IGBT converter with two separate inverters and a system ensuring a phase-shifted operation of the furnace coil sections. In the charge melt-down phase the furnace can thus be run at an appropriate nominal frequency of e.g. 250 Hz and for increased bath agitation at low power the frequency can be steplessly adjusted below 100 Hz. The amount of phase offset between the two coil sections is likewise adjustable to provide a selective control of the flow pattern (i.e. direction of rotation and velocity) in the central coil area of the furnace. This way, the region of maximum flow velocity can be moved into the interior of the molten metal bath and more effective intermixing of the entire melt will occur. The technical options available for influencing bath movement in a coreless induction furnace can be implemented and combined in manifold ways to address specific metallurgical tasks, as is summarized in Table 1.

### TYPICAL SUCCESSFUL APPLICATIONS

The fundamental requirements for melting down small-sized charge materials can be summarized as follows: The focus is on minimum metal loss, high energy efficiency, reliability in operation, low environmental pollution and optimum efficiency, no matter whether foil, punching, slab milling chips or machining chips of castings or ferroalloy fines need to be melted. Appropriate melting applications in one's own company, so-called in-house recycling, also gains increasing significance.

The following describes just a few of the numerous successful applications of coreless medium-frequency induction furnaces for melting such types of charge material.

### RECYCLING OF FINE-SIZED ALUMINIUM

#### Slab milling chips

In this case, an induction furnace plant is to be used for the melting down of dry milling chips of the AlMg₅ alloy of which large quantities are produced in the machining of continuously cast slabs. The specific surface area of the chips of 1.97 m²/kg is relatively small and the oxide content of slightly above 1 % is not really high.

Apart from low energy consumption and low metal losses the melting plant was expected to ensure high equipment availability and in particular a refractory lifetime of more than one year.

In order to reach this target the new medium-frequency furnace plant has been equipped with the Power-Focus feature for selective power concentration and with variable operating frequency. In this way, the power input can be focused on specific coil areas and the operating frequency is variable as a function of bath level and power input. Moreover, the structure-borne noise and thus the vibration of the furnace body is measured as well. If these values are too high the power input is reduced in order to protect the refractory lining.

The technical data of the furnace system used are as follows:
- Capacity 7.5 t, rated power 2,600 kW, frequency 80 Hz or 110 Hz selectable

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<td>Promoting chemical surface reactions</td>
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<td><strong>Process-oriented IGBT technology</strong></td>
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<td>Variable frequency (e.g. 250 Hz, stepless adjustment from 100–33 Hz) plus use of multiple coil sections with phase-shifted power supply</td>
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<td>Pilot plants for determining optimum process windows regarding heat input and flow velocity</td>
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Chip input from storage bin via chute with controlled feed rate
Automatic furnace control using the JOKS melt processor.

The furnace is operated in such a way that metal is tapped down to a heel of 4.5 t and then charged of the chips commences. For this the equipment parameters are set such as to ensure that the chips are stirred down swiftly and with low bath level the Power-Focus system is used to concentrate power on the lower region of the coil. When the furnace is nearly full, the frequency is reduced in order to maintain sufficiently strong bath movement for stirring-down the chips quickly.

Recycling of machining chips
A tremendous amount of chips and swarf with adhesive coolant is produced in the machining of car wheels made from ALSi9Mg alloy castings. After treatment in a centrifuge, the chips still contain a residual amount of machining emulsion in the order of 1–2 %. The requirement was to perform melting operation in-house with melting losses below 1.5 % and with low energy consumption.

The system of choice was a medium-frequency melting furnace with a capacity of 3 t and a power rating of 1,200 kW. The operating frequency ranges from 110–150 Hz. From a chip preparation system with storage bin and attached screw feeder, the chips are fed to the melting furnace continuously. The chips enter the furnace through a swing-type lid with funnel-shaped opening (Fig. 4). Again, the furnace is started with a heel and the system is controlled such as to ensure quick stirring down of the chips without overfilling the furnace. The JOKS melt processor makes sure that any overheating of the melt beyond 780 °C is ruled out. The furnace plant has been in operation with great success since several years, fully meeting the target.

Recycling of aluminium foil
This plant in Italy – comprising a 5.5 t furnace with a power rating of 1,500 kW at 70 Hz – is used exclusively for the melting of baled foil (Fig. 5) of the 8006 alloy (pure aluminium with about 0.4 % of manganese).

The foil bales of 300 x 300 x 400 mm are slightly compressed and contain rolling oil residues of up to 2 %. The bales are charged into the furnace intermittently by belt conveyor, starting with a heel of about 50 %. Furnace power and charge input are controlled in such a way that the bales are embedded in the molten metal of the heel while the bath surface is permanently covered with bales.

Upon complete melting of the charge, the bath surface looks clean, bright and covered with just a thin oxide layer. Finally, the metal is tapped into a launder without prior dross skimming. The launder transfers the molten metal either to a gas-fired holding furnace or to an ingot mould.

As virtually, no dross develops during the melting cycle the melting losses are negligible. In addition, there is no need for cleaning the crucible wall, simply because there are no dross accretions.

The refractory lifetime is more than six months and the output is around 5,000 t per lining campaign. The results are most remarkable, the more so as the charge material has a very unfavourable surface area to volume ratio.

MELTING OF WET BRASS CHIPS
The recycling of brass chips from the mechanical machining process forms a traditional part of the melting programme in the copper semis industry. While channel-type induction furnaces were predominantly used in the 1970s to melt such chips, this changed at the beginning of the 1980s. The benefits of the coreless induction furnace with its bath movement that can be varied via the specific power and frequency and the resulting stirring effect can be advantageously and systematically exploited here. Due to its greater profitability, the coreless-type furnace came to replace the channel-type furnace for the recycling of chips, and ever-larger coreless induction furnaces were employed to achieve ever-higher melting capacities.

Since the chips are normally delivered damp, however, the commonly practiced recycling of brass chips required the chips to be dried before melting in both the channel-type furnace and the coreless-type furnace. While there is no alternative to this in a channel induction furnace, the coreless induction furnace as basic component offers the possibility of charging chips damp. In this case, however, not only the coreless furnace with the chip charging system, furnace hood and flue gas ducting have to be included as integral parts of the process, but also a process...
control and automation system geared to the chip type and the performance capabilities of the individual plant components is necessary. The resulting economic benefits are enormous, since not only can the whole investment-, time- and energy-intensive drying process be completely eliminated, but also the oil adhering to the chips can be at least partially used for the melting process.

The brass chip as a recycling charge material
Brass chips are created in very large quantities during the mechanical further processing of brass blanks to form intermediates or final parts. This results in a need for internal recycling, particularly in the semis production plants. But since chips are also offered as a cheap raw material and frequently have to be taken back from external finishers of the intermediates, the efficient processing of chips has taken a considerable economic significance.

Compared to the melting of lump scrap or ingots, the melting of chips is more difficult to control and involves greater metal losses and higher specific energy consumptions. This is related in particular to the shape of the chips and their low bulk density. Consequently, unconditioned chips charged onto a static melt clog together, oxidize strongly and then tend – particularly in high performance coreless-type furnaces – to establish dangerous bridges.

A further aspect is the moisture adhering to the chips; it consists of emulsions whose exact composition depends on the further treatment process in question. However, the oil content of chips from turning, milling and drilling processes is not inconsiderable. In practice, chips are recycled with a moisture content of up to 6–8 %. With the conventional further processing, a previous centrifuging and drying is therefore unavoidable. These drying plants consist of large rotating drums into which the chips are charged in batches. By heating the outer shell of the rotating drum using gas burners, the chips inside the drum are heated so that the adhering moisture evaporates. Evaporating oil creates harmful hydrocarbons that have to be treated in these plants to make them safe by means of post-combustion installations (thermal post-combustion at approx. 900 °C) at the upper end of the stack. The conventional drying process thus involves additional costs at approx. 10 €/t for the recycling of chips in the form of:

- Personnel costs for the chip transport and plant operation
- Heating energy costs for the heating of the chips and for the thermal post-combustion
- Space costs for the predrying plant
- Maintenance costs for the predrying plant.

Finally, the chips are contaminated with foreign metals since they normally contain some percentage of iron and tin, in particular. This makes the melting of 100 % chips difficult and necessitates a continuous quality control.

The charging of damp chips
If chips are to be charged damp, measures must be taken to reliably prevent any notable quantities of emulsion being trapped in the liquid metal. This is effected in practice by a continuous charging of the chips at a rate matched exactly to the melting rate, whereby the drop height of the chips is designed such as to allow an adequate predrying with rapid combustion of the oil contents before the chips are stirred into the melt.

For this, the charging system has to be designed with respect to the density and structure of the brass chips to be handled. In practice, both, very short and extremely wet chips with comparatively high bulk densities are encountered, as are bales of chips with extremely low densities. When designing the chip charging systems, attention therefore has to be paid to the chip grades that are to be melted, and whether these grades change frequently. Such a chip charging system is typically composed of the following components:

- Main storage bunker
- Coarse screen for separating coarse or non-metallic materials
- Magnetic separator for removing ferrous constituents such as drills, iron chips etc.
- Chips transport system to furnace charging level
- Intermediate bunker at charging level
- Metering unit for establishing controlled chip charging into the melting furnace.

It is very important that charging happens smoothly and that it strictly follows the melting capacity of the furnace.
The coreless furnace as chip melter
Due to their low density, the chips would remain on the bath surface during charging on a stationary metal bath surface because typically there is a dross layer that covers the liquid metal bath and separates the chips from the liquid melt underneath. Without mechanical stirring or ramming, the chips cannot break through this dross layer to enter into the melt.

With the coreless-type furnace, this problem is solved by stirring the bath due to induction forces, as described above. An appropriate dimensioning by matching the coil height and coil diameter in conjunction with an operation near the mains-frequency (50–70 Hz) at a sufficiently high specific power allows a sufficient mechanical stirring effect to be created within the melt just by induction. As described, this stirring effect results in two opposed metal flow patterns in the coreless-type furnace. In the upper part of the bath, the melt is pushed in the middle up to the bath surface and from there towards the crucible walls. As a result, the unavoidable dross layer on the bath surface is pushed towards the crucible walls and allows the brass chips to be charged into the dross-free centre of the liquid melt. From here, they are readily encapsulated by liquid metal and melted down withdrawing heat from the metal bath.

The exhaust systems
The combustion of the oils or emulsions adhering to the chips generates exhaust gas temperatures in the furnace hood that can be well above 1,000 °C. A ceramic lining of the furnace hood is therefore mandatory. Furthermore, suitable measures have to be taken to control the combustion and to guide the exhaust gases safely and spark-free to the baghouse.

On the other hand, however, these high combustion temperatures in the furnace hood guarantee a complete oxidizing combustion of the oil adhering to the chips without formation of harmful hydrocarbons. This allows cost-intensive thermal post-combustion in the exhaust system to be eliminated.

When the exhaust gases leave the furnace hood, the hot gases have to be cooled correspondingly quickly in order to avoid the secondary creation of harmful organics and to prevent exceeding the allowed filter temperature in the baghouse. Therefore, the first part of the exhaust pipework is water-cooled and a subsequent fresh air suction regulated by an air flap forcing a fast and drastic temperature drop after the gases leave the furnace hood (Fig. 6 and Fig. 7). Further downstream zinc-oxide fines and sparks...
are removed in a cyclone and safety equipment like spark detector and extinguisher follow before the gas enters the baghouse (Fig. 7).

The chip melting process

The quality and results of the process of melting damp brass chips depend on the optimum balance of charging, melting and off-gas control.

First of all, the coreless furnace has a certain swallowing capacity, which depends on its operational parameters, basically its filling level and its effective power. Next, the charging system has to be matched to the chip grade and has to compensate changing chip densities by varying the charging speed. The charging speed, in turn, has to take account of the available furnace power at all times. In general, the available furnace power depends on its filling grade, starting with about 70 % of the furnace nominal power rate and ending up with 100 % as soon as the filling level reaches around 80 % of the coil height. The swallowing capacity describes the maximum volume of chips per unit of time that the coreless-type furnace can stir in and melt at any point during the charging process.

In order to synchronize the individual process steps during the melting of damp chips, the coreless-type furnace is put on load cells and controlled via a melt processor and a PLC. These process the signals from the charging system and the furnace, here e. g. by a continuous measurement of the furnace weight and permanent monitoring of the available furnace power and hence control the melting process until the furnace is filled up to the coil rim. Thereafter, lumpy scrap can be charged to fill up the furnace completely.

Practical results

Characteristic key data for chip processing are the metal yield, influenced by the metal losses caused by oxidation and evaporation, and the specific power consumption for melting.

Experience in practice has shown that the metal losses during melting of brass chips are in the order of 1–3 %. In view of the 5–6 % losses in channel furnaces plus an additional 1 % during predrying, this value speaks for itself and offers an excellent basis for new investments [2].

Regarding the power consumption, figures from plants in practice show values between 270 and 320 kWh/t. The lower value here refers to furnaces with capacities of ≥ 12 t while the higher value refers to smaller furnaces with 3–4 t capacity.

Recycling of ferroalloy fines

In breaking ferroalloy ingots – e. g. ferrosilicon or silicomanganese – obtained in submerged arc furnaces, a 0–13 mm grain size fraction (fines) is obtained in substantial amounts. However, this material cannot be usefully employed for metallurgical purposes. Similarly, it makes no sense either economically or technically to reintroduce it into the smelting process. As a result, these fines are typically disposed off as waste.

As far as recycling in a coreless induction furnace is concerned, the situation is complicated by two specific facts when compared to the remelting of chips and foils discussed above: On the one hand, these alloys will not couple to the electromagnetic field at suitable operating frequencies while in a solid state, whereas in a liquid state they will. As a result, solid charge material cannot be melted down directly but only indirectly in a heel of molten metal. Furthermore, this implies that after a furnace relining, the refractory material needs to be sintered with a ferroalloy melt by a process referred to as liquid sintering.

On the other hand, these fines contain up to 15 % non-metallic components – mainly SiO₂ and Al₂O₃ in the case of ferrosilicon. Substantial amounts of slag will therefore form when such fines are melted down, and the viscosity of this slag is highly dependent on its composition and temperature. In the case of a coreless induction furnace conventionally rated (e. g. for cast iron or steel) in terms of a given capacity, power and frequency ratio there is a risk that the slag thus formed, which we shall initially assume to be of low viscosity here, will accumulate in the annular gap between the meniscus and crucible wall where it will float on the moving melt because it is of lower density than the metal. This molten slag will continue to accumulate and eventually begin to cover the entire bath. At this point the latest, melting must be discontinued as the charge material will drop onto the slag, cooling it down and thus in turn increasing its viscosity. A process of this type will hence be characterized by frequent melting interruptions and laborious deslagging. The situation described above applies to slag of an assumed low viscosity. In practice, however, the slag will not be of such low viscosity due to the composition of slag-forming agents present in the charge. As a result, the problem described above will be aggravated further.

In the light of these considerations and experience, a coreless furnace running at a low frequency and having a geometry promoting optimum bath movement was designed for the present task. Moreover, it was envisaged to add slag formers along with the charge material – based on the relevant phase diagrams – so as to reduce the melting temperature of the slag and hence, its viscosity at the operating temperature. Through these measures it proved possible, starting out from a heel level of 50 %, to run a continuous melting process without any intermediate deslagging until the furnace was filled to nominal capacity. The highly liquid slag could be poured off without any problems. This was facilitated by the intense bath movement, which was
strong enough for the slag to be drawn down into the melt over and over again so as to retain the bath temperature. One indispensable requirement in a regime of this type is that the melting process must not be interrupted by any means, for the slag would otherwise rise up immediately in the absence of bath movement and would then form a liquid top seal that is impenetrable to the melt upon restarting. Deslagging would then have to be carried out before continuing the melting cycle, although it had been the stated objective to avoid just that.

The furnace has a capacity of 3,000 kg relating to FeSi 75 and features a 250 Hz / 125 Hz multi-frequency capability. In the first trials it achieved a melting rate of over 2 t/h at a reduced power input. **Fig. 8** shows a view into the crucible during the melting process. The charge material was drawn from a suitable hopper via a shaker chute.

**Melt refining system**

In this case, Otto Junker was entrusted with the task of designing a coreless furnace capable of carrying out a melt

**Fig. 8:** Melting down ferrosilicon fines

**Fig. 9:** Impact of power, operating frequency and phase angle of currents in the coil sections on the intensity and patterns of bath movement
refinement process involving plasma surface treatment. Once the furnace was filled to its nominal capacity, an active gas plasma was to be applied to the melt surface. The surface bath movement and hence, mass transfer was to be maximized while metal spillage was nevertheless to be avoided. At the same time, the temperature was to be kept as constant as possible over a treatment cycle of several hours, taking into account the heat input caused by the plasma burner.

Based on this specification, a furnace system with a crucible capacity of around 100 l was designed, built and commissioned. Along with a conventional melting mode (230 Hz, 300 kW), this system provides a stirring mode at reduced heat input in which the frequency and power input are steplessly adjustable independently of each other. The operating frequency ranges from 30–100 Hz, i.e. starting out from a bottom value below the mains-frequency. Moreover, in stirring mode the two coil sections of this furnace system can be operated at two different phase angles in the manner known, e.g. from linear motors.

This design provides hitherto unknown flexibility as regards to the independent control of its thermal power input and melt flow characteristics. An illustration of this is given in Fig. 9 for the example of an aluminium melting operation. Fig. 9a illustrates the situation in melting mode at a power input of 120 kW and an operating frequency of 230 Hz. Fig. 9b–d depict conditions at 28 kW / 34 Hz and a phase angle of 0°, +90° and –90°, respectively.

A comparison between Fig. 9a and Figs. 9b–d makes the role of the operating frequency impressively clear. At 34 Hz, a mere 28 kW of power suffices to produce approx. the same flow velocity in the bath as at 230 Hz and 128 kW. Moreover, Fig. 9b–d graphically illustrate the impact of the phase angle on bath movement.

The furnace system fulfills its intended operating purpose in a fully satisfactory manner, yet the technology employed here opens up much wider perspectives. On the one hand, the low-frequency operating regime in conjunction with a phase shift enables engineers to design high-turbulence induction mixers providing ideal conditions for metal-slag reactions. At the same time, the increased magnetic penetration depth obtained at the low frequency supports the choice of a much thicker crucible wall compared to conventional coreless furnaces, which is an indispensable requirement for such metallurgical tasks. Fields of application include e.g. secondary metallurgical operations in steelmaking or copper refining steps in making semi-finished products. Moreover, this technology necessarily provides benefits when it comes to recycling fines, as described above.

CONCLUSION
Continuous improvements in induction furnace technology, especially in the field of frequency converter systems, have greatly expanded its range of process application options.

Accordingly, the induction furnace merely represents an advanced and very powerful standard melting resource today, tailor-made designs are increasingly being employed to address specific metallurgical tasks. To sum up, it may be stated that the medium-frequency coreless furnace has evolved into a melting system meeting nearly universal requirements.

LITERATURE


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