Development and Use of a New Optical Sensor System for Induction Furnace Crucible Monitoring

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Abstract

Dependable protection of the induction coil against overheating and, the more so, against contact with molten metal is of vital importance for ensuring safe and reliable operation of an induction furnace.

Addressing this requirement, various technical solutions for monitoring the refractory crucible condition were proposed and implemented in the past but an optimum solution has not been found as yet.

The present paper describes the development and use of a totally new temperature measuring and monitoring system. The new system uses fibre-optical sensors which are particularly suitable for interference-free crucible monitoring in induction melting furnace applications, and provide direct and independent temperature field measurement in the immediate vicinity of the induction coil.

Following months of experiments in the test bay during which all minor problems were duly identified and remedied, long-term tests were conducted in several furnaces under production conditions.

The result can be summarised as follows: Crucible cracks and erosion are detected and localised reliably and precisely and normal refractory wear is under close control.

Key words

induction furnace; crucible monitoring system; fibre-optical sensors

Introduction

One key design feature distinguishing induction furnaces from other heating equipment is the fairly thin ceramic lining between the live water-cooled copper conductor and the molten metal bath (Fig.1). Depending on the furnace size, the thickness of this ceramic lining varies between 10 and 15 cm; it diminishes noticeably as a result of wear or crucible erosion. Inductor insulating materials such as insulating varnish and bandages are heat resistant up to about 150 - 200 °C. If overheating occurs at this point, the insulation may become damaged or even electrically conductive, resulting in interturn short-circuiting of the coil. The coil repair effort required in this case will render the furnace inoperative for several days, even if a spare coil is on hand. In the worst case, which has rarely been documented but is nevertheless a possibility, the melt may penetrate all the way through to the water-cooled coil with all attendant risks of a furnace breakthrough and ultimately, a steam explosion.

These considerations, together with furnace users' economically motivated demands for a maximum service life of the ceramic furnace lining, call for a technology which permits a "visual" inspection of the gap between the ceramic furnace lining and the induction coil. Addressing this requirement, various technical solutions for monitoring the crucible have been proposed and implemented in the past.

Overview of conventional crucible monitoring systems

The most important of these is the classic earth leakage monitoring system. In this technology, a d.c. or a.c. voltage of a defined, fairly low frequency is applied to the induction coil and the system measures the current flow to earth. For this purpose the molten metal bath must be earthed via an earthing rod in the bottom of the crucible. This earth fault monitoring system, although by now a standard feature on virtually all induction furnaces, has a number of disadvantages. For one, it is not selective, i.e., defined tests and disconnection steps must be carried out whenever an earth leakage is detected so as to determine whether the fault has occurred between the coil and the molten metal or in any other part of the equipment, such as in the switchgear or even in the water recooling system. Another disadvantage of this earth leakage monitoring method is that in the event of infiltration or penetration of molten metal to the coil, evidence of this condition will be not be obtained until fairly late. As a result, the furnace must be emptied quickly if a current flow between the melt and the coil is detected. In any event, minor damage to the coil may have occurred already.

The use of thermocouples between the hot-face lining and the coil levelling mix, as well as in the furnace bottom, is another technique employed. However, this method can yield only spot measurements and is therefore not capable of monitoring the entire crucible.

In the past, wire netting in various geometrical configurations has been placed between the coil levelling mix and the hot face lining. The idea is to detect an electrical continuity between an advancing tip of molten metal and the net. One particular disadvantage of this method is that it provides no trend indication, i.e., no advance warning is given.

A further process in industrial use [1, 2] relies on the use of sensor grids comprising an array of metallic electrodes in a comb-type configuration. These electrodes are used to measure the electrical resistance of the ceramic lining. As this resistance is temperature-related, it is possible to infer the temperature in specific crucible segments. Fault locations can thus be identified in relation to the furnace circumference, and an advance warning functionality is obtained. However, spatial resolution is limited (typical system: 8 radial segments, no height information) and the readings are affected by conductivity changes of the refractory not caused by temperature (e.g. moisture, Zn deposits).

OCP Optical Coil Protection System

OCP (Optical Coil Protection System) stands for a latest-generation temperature measurement and monitoring technology which relies on fibre-optic sensors. Given their properties, such sensors are perfectly suited for interference-free monitoring of the crucible on induction melting furnaces. Based on an optical fibre, the system utilizes a quantum-mechanical effect, the so-called RAMAN effect, for temperature measurement [3]. Laser light of a suitable wavelength and modulation frequency is injected into the optical fibre. This laser light scatters on the bonding electrons of the solid state structure over the full fibre length and is detected as a backscatter spectrum. This spectrum contains the RAMAN lines, the intensity of which is a function of vibration levels in the solid state fibre structure, which in turn depend on temperature. A new, patented 'optical radar' technique makes it possible to detect these lines locally and to measure an exact, high-resolution temperature profile through the optical fibre. Thus, OCP is a unique crucible monitoring system which enables us for the first time ever to determine the temperature field in the induction furnace irrespective of refractory type and design. By selecting a radial resolution of 60 measuring points, it is possible to represent the temperature curve in the manner of the familiar analogue clockface (Fig. 2). By adopting an appropriate configuration of the sensor grids, the crucible can be vertically divided into several regions, although only a single optical fibre is used in all cases. Points of particularly high temperature, e.g., due to infiltration, erosion or cracking in the crucible, can thus be accurately localized and checked for potential hazards to the coil insulation.

Design and installation of the OCP sensor cable

The core of the OCP sensor cable, first of all, consists of a commercially available high-temperature glass fibre of the type commonly used in telecommunications. For mechanical protection, this fibre is enclosed in a stainless steel tube measuring 1.2 mm in diameter. The tube, in turn, is coated with a high-temperature insulating compound. The overall diameter of the sensor cable is 5 mm.

In order to provide the fullest possible crucible sensor coverage in the direct vicinity of the coil, it is desirable to have a maximum length of sensor cable in the furnace. This is achieved by placing the sensor cable on the inside of the coil in meandering curves. Fig. 3 illustrates this layout on a 12-tonne cast iron melting furnace. Here we have four meandering cable layers. Once the cable is installed in this manner, the usual former is placed in the coil and a permanent lining made of high temperature resistant corundum concrete is cast, with the sensor cable thus embedded therein. In a next step, the intended measuring end of the sensor cable is connected to an optical fibre transfer cable armoured to foundry standards. This cable is run to the location of the evaluator and connected to one of its ports.

Display of measured temperature data

The main screen of the OCP visualization system is shown in Fig. 2. It displays a schematic top-down view of two furnaces, each comprising two or more meander layers. If more than two furnaces are monitored, the user can freely select which of these should be displayed on the left and right-hand side, respectively. As a general rule, the temperature curves for all individual meander layers are initially rendered in a screen window. For a less cluttered view, individual layers can be suppressed. This has been done in Fig. 2, where the left image shows the current temperature distribution in the upper layer of Furnace 1 while the image on the right gives the current temperature distribution in the bottom layer of Furnace 2. Each of these temperature profiles can be rendered in a polar or linear view. It is also possible to display a "relative" mode, i.e., a profile generated in relation to a given historical (reference) profile. In this case the user will see the current temperature deviation from the selected reference profile (offset view).

By selecting a playback function and entering a date in the respective window, past temperature profiles can be viewed at any time. It is also possible to show temperature profiles in an animated or "video" mode between a user-defined start and end point. Also the temperature history of selected measurement points can be displayed.

Evaluation of temperature measurements

Four types of alarm algorithms can be configured offering several parameters to be adjusted. For every parameter, the user can enter a warning threshold and an alarm trigger threshold. The individual alarm criteria are monitored as follows:

1. Temperature

The temperatures at one or more measuring points are monitored for overruns exceeding these preset thresholds.

2. Deviation from average

The measurements from which the temperature profile is plotted are initially processed into an average value representing the mean temperature in the respective zone. The system then checks whether the temperature at one or more measuring points deviates from this mean value by more than the preset threshold.

3. *Temperature change*

Here the system determines whether a time-related temperature gradient, defined as a threshold, is exceeded at one or more measuring points. The unit in which this threshold is set in the various input fields is °C/min.

4. *Uniformity*

The uniformity parameter is largely identical with the "deviation from average" criterion, except that the averaging step and check for threshold overruns is not carried out in a single step over the entire circumference of the furnace. Instead, the system initially examines a radial sector ("pie wedge") whose thickness is defined by the user in angular degrees (°) in the window marked "step". This sector is then analyzed in the same way as for the "deviation from average" criterion. In an interactive process, this evaluation window is then advanced in a clockwise direction one measuring point at a time. The analysis is continued until the evaluation window has covered the entire circumference of the furnace. This is a valuable criterion when it comes to distinguishing local flaws from large erosion areas.

Practical operating examples

OCP systems are now successfully in use in coreless induction furnaces for melting copper alloys, aluminium alloys, cast iron and steel. In the following part of this paper three exemplary cases will be examined in which crucible wear and premature crucible failures were detected in a timely and accurate manner.

2.5-tonne vacuum-type coreless induction furnace for melting copper pre-alloys

This particular furnace is run in three-shifts to produce copper-iron pre-alloys. Such alloys pose exacting demands on the crucible material due to their aggressive chemical characteristics and fluidity. The tapping temperature is in the region of 1500 °C. The furnace is usually operated with a ready-made crucible consisting of refractory concrete. The space between this crucible and the coil is backfilled with a dry ramming compound. A normal crucible campaign lasts about 2 weeks, depending largely on the degree of sintering of the backfill mix. If sintering propagated too far towards the coil the crucible will be very difficult to break out; moreover, there will be an increased likelihood of molten metal penetrating all the way to the coil in the event of a crack formation in the crucible. The degree of backfill mix sintering grows over the crucible campaign, causing the thermal conductivity of the backfilling material to increase progressively. As a result, the temperature in the permanent furnace lining and hence, the temperature local to the OCP sensor cable, will rise steadily. Fig. 4 shows the temperature profile at the start (left) and near the end (right) of a normal crucible campaign in which no apparent local crucible failure occurred. Once a critical maximum temperature had been identified over several crucible campaigns, the OCP system was used as an indicator to identify the need for a scheduled re-lining. Fig. 5 shows the situation for a crucible that had been in use for a week, i.e., half the normal crucible campaign. The graph on the left plots the absolute temperatures; its right-hand side counterpart gives an offset view of the same development. Over a span of a few charges, overtemperatures increasing from one charge to the next were identified in the 5 o'clock position, and the system eventually generated alarms of the "deviation from average" type. The crucible was broken out, and a crack was found at this point which had allowed the melt to infiltrate the ramming compound.

6-tonne coreless induction furnace for melting stainless steel

Fig. 6 shows the temperature profile measured in the lower regions of a 6-tonne induction furnace for steel near the end of a crucible campaign. The "deviation from average" alarm messages (left) indicate general erosion towards the furnace spout. The "uniformity alarm" messages (right) point to the formation of caverns at four points. Dimensional measurements conducted on this crucible prior to break-out confirmed the condition detected by the OCP system (Fig. 7).

Detection of cracks in the crucible

When a crucible cools down, e.g., over a weekend, numerous cooling cracks will form naturally due to volumetric contraction of the crucible material. These cracks will normally close again, due to thermal expansion of the crucible material, the next time the furnace is started up. However, an appropriate heating curve must be used to ensure this. Otherwise, the progressively melting metal may spontaneously penetrate still-open cracks and come dangerously close to the coil. The situation becomes even more critical if the furnace is filled with liquid metal before the cracks have closed.

To simulate this situation, the following test was carried out: A thick-walled steel cylinder of a diameter equivalent to the inside diameter of the crucibles normally used in this application was placed in the middle of an unlined 1-tonne-furnace. This steel cylinder exhibited "artificial cracks" at a level about halfway up the furnace coil, these being in the form of 5 mm thick and 100 mm wide pieces of steel plate welded to the cylinder in the 12, 3 and 9 o'clock positions. The plate in the 3 o'clock position was welded to the surface horizontally and ended about 10 mm short of the furnace's permanent lining. An identical plate was welded on in the 12 o'clock position, but in a vertical direction. In the 9 o'clock position there was another horizontal plate which extended to the permanent lining. Finally, a 100 x 100 x 30 mm steel plate representing a cavern was welded to the cylinder in the 6 o'clock position. Fig. 8 shows a sketch of this arrangement. The space between the steel cylinder and the furnace's permanent lining was filled with a quartzite dry ramming compound. The furnace was then switched on and operated at about 350 kW. This procedure was intended to simulate a cold start with existing metal-filled cracks. After 30 minutes, all "crucible defects" are clearly identifiable and reported by the corresponding alarm messages (Fig. 9). It should be mentioned that the small test furnace allowed to embed only a one-layer sensor cable of limited length, which gives an inferior position resolution. The position resolution will naturally be higher on a larger furnace. However, the unusually good temperature resolution of the measuring method is impressively demonstrated.

Conclusions

The essential advantages of the Optical Coil Protection (OCP) system can thus be summarized in the following key-words:

- Full protection against
  Operational breakdown due to coil damage
  Bodily injury and equipment damage due to molten metal breakthrough
- Recording and visualization of the temperature profile over the entire crucible campaign
  Indication of developments and trends of refractory wear or metal penetration
  Possibility to take action in good time to extend refractory life
- Direct temperature measurement, not resistance-based
  Fully operational with a vast range of refractories and immediately after relining
- Optical (i.e., non-electrical) measuring method
  Eliminates false signals or even sensor grid damage by the magnetic field of the induction furnace
- One single evaluator can monitor up two four furnaces
- Very high resolution, e.g. 60 spots over the circumference of an 8-tonne-furnace crucible, like the second marks on a clockface
- Temperature measurement with a resolution better than 1 K
- This distributed optical-fibre temperature measuring method has evolved into a mature system which has been demonstrating its reliability as a central safety system for years in more than 300 installations worldwide [4].

References

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3. Dr.-Ing. Glombitza U, *„Verfahren zur Auswertung optisch rückgestreuter Signale zur Bestimmung eines streckenabhängigen Meßprofils eines Rückstreumediums“* EP 0692705, 1995
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Figures

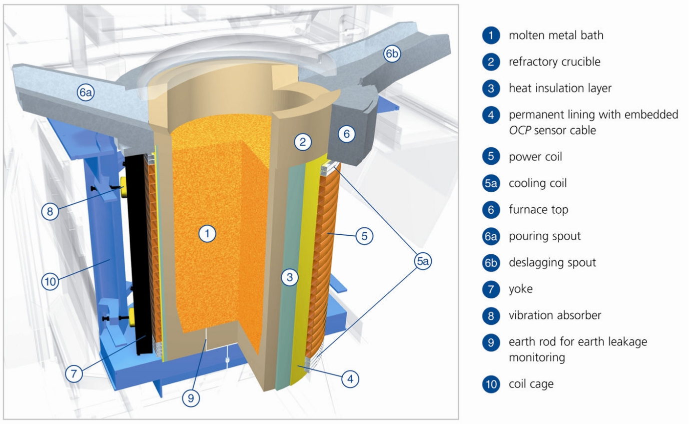
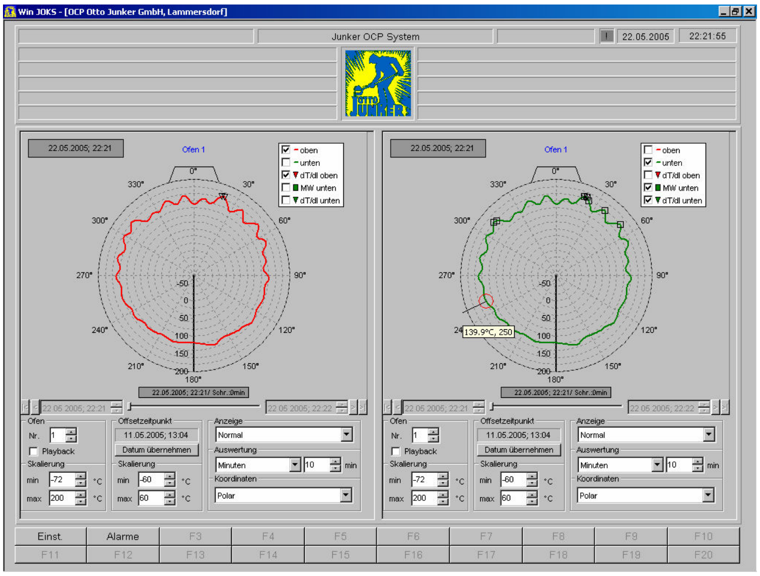


Fig. 1 View of a typical crucible structure, showing the permanent furnace lining with the OCP sensor cable embedded ④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Junker OCP System 22.05.2005 22:21:55

22.05.2005; 22:21 Ofen 1
☑ oben
☐ unten
☑ dT/dl oben
☐ MW unten
☐ dT/dl unten

22.05.2005; 22:21/ Schr.:0min

Ofen Nr. 1
☐ Playback
Skalierung min -72 °C max 200 °C
Offsetzeitpunkt 11.05.2005; 13:04
Skalierung min -60 °C max 60 °C
Anzeige Normal
Auswertung Minuten 10 min
Koordinaten Polar

22.05.2005; 22:21 Ofen 1
☐ oben
☑ unten
☐ dT/dl oben
☑ MW unten
☑ dT/dl unten

139.9°C, 250

22.05.2005; 22:21/ Schr.:0min

Ofen Nr. 1
☐ Playback
Skalierung min -72 °C max 200 °C
Offsetzeitpunkt 11.05.2005; 13:04
Skalierung min -60 °C max 60 °C
Anzeige Normal
Auswertung Minuten 10 min
Koordinaten Polar

Fig. 2 OCP System monitor screen

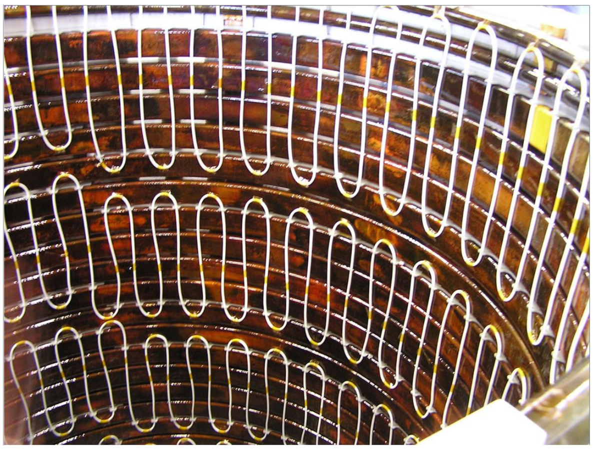
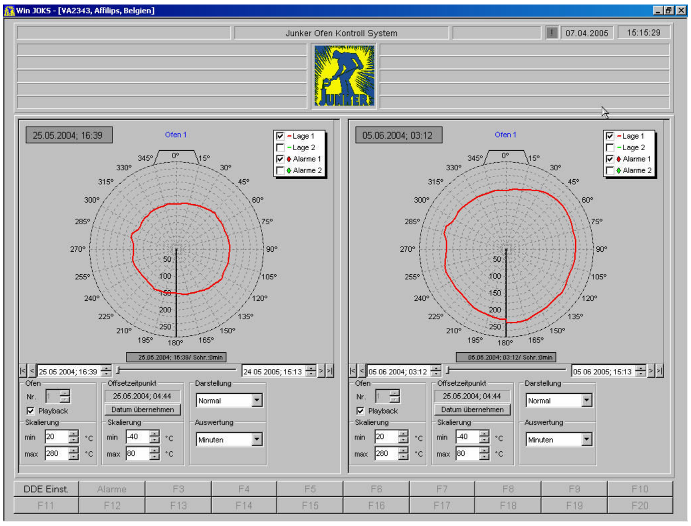


Fig. 3 Arrangement of the OCP sensor cable on the coil of a 6-tonne induction furnace or melting steel



Win JOKS - [VA2343, Affilips, Belgien]

Junker Ofen Kontroll System 07.04.2005 15:15:29

25.05.2004; 16:39 — Ofen 1 — ☑ Lage 1 ☐ Lage 2 ☑ Alarme 1 ☐ Alarme 2

25.05.2004; 16:39/ Schr.:0min

25 05 2004; 16:39 — 24 05 2005; 15:13

Ofen Nr. 1 ☑ Playback; Skalierung min 20 °C max 280 °C

Offsetzeitpunkt 25.05.2004; 04:44 Datum übernehmen; Skalierung min -40 °C max 80 °C

Darstellung Normal; Auswertung Minuten

05.06.2004; 03:12 — Ofen 1 — ☑ Lage 1 ☐ Lage 2 ☑ Alarme 1 ☐ Alarme 2

05.06.2004; 03:12/ Schr.:0min

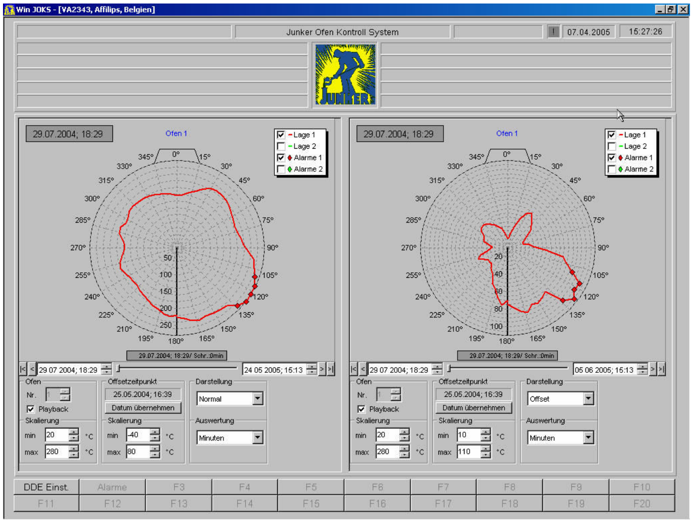
05 06 2004; 03:12 — 05 06 2005; 15:13

Ofen Nr. 1 ☑ Playback; Skalierung min 20 °C max 280 °C

Offsetzeitpunkt 25.05.2004; 04:44 Datum übernehmen; Skalierung min -40 °C max 80 °C

Darstellung Normal; Auswertung Minuten

Fig. 4 Temperature profiles on a 2.5-tonne vacuum-type induction furnace at the start (left) and end (right) of a trouble-free crucible campaign



Win JOKS - [VA2343, Affilips, Belgien]

Junker Ofen Kontroll System 07.04.2005 15:27:26

29.07.2004; 18:29 — Ofen 1 — ☑ Lage 1 ☐ Lage 2 ☑ Alarme 1 ☐ Alarme 2

29.07.2004; 18:29/ Schr.:0min

29 07 2004; 18:29 — 24 05 2005; 15:13

Ofen Nr. 1 ☑ Playback; Skalierung min 20 °C max 280 °C

Offsetzeitpunkt 25.05.2004; 16:39 Datum übernehmen; Skalierung min -40 °C max 80 °C

Darstellung Normal; Auswertung Minuten

29.07.2004; 18:29 — Ofen 1 — ☑ Lage 1 ☐ Lage 2 ☑ Alarme 1 ☐ Alarme 2

29.07.2004; 18:29/ Schr.:0min

29 07 2004; 18:29 — 05 06 2005; 15:13

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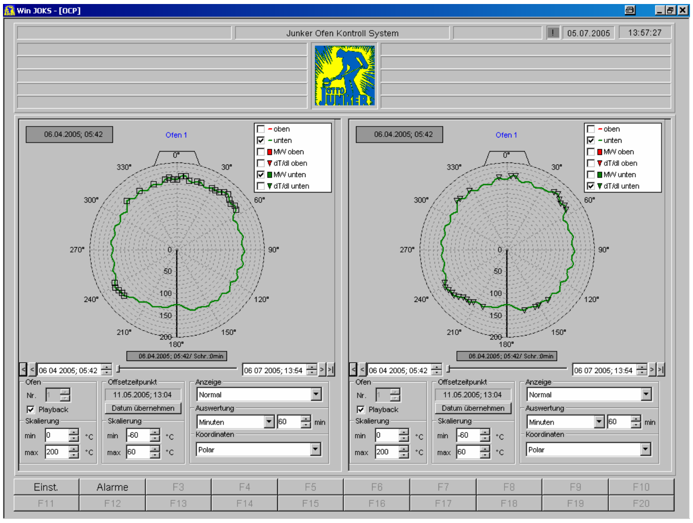
Offsetzeitpunkt 25.05.2004; 16:39 Datum übernehmen; Skalierung min 10 °C max 110 °C

Darstellung Offset; Auswertung Minuten

Fig. 5 Temperature profiles obtained after crucible cracking with resultant infiltration; absolute temperature (left) and offset display mode (right)



Win JOKS - [OCP]

Junker Ofen Kontroll System 05.07.2005 13:57:27

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06.04.2005; 05:42/ Schr.:0min

06 04 2005; 05:42 — 06 07 2005; 13:54

Ofen Nr. 1 ☑ Playback; Skalierung min 0 °C max 200 °C

Offsetzeitpunkt 11.05.2005; 13:04 Datum übernehmen; Skalierung min -60 °C max 60 °C

Anzeige Normal; Auswertung Minuten 60 min; Koordinaten Polar

06.04.2005; 05:42 — Ofen 1 — ☐ oben ☑ unten ☐ MW oben ☐ dT/dt oben ☐ MW unten ☑ dT/dt unten

06.04.2005; 05:42/ Schr.:0min

06 04 2005; 05:42 — 06 07 2005; 13:54

Ofen Nr. 1 ☑ Playback; Skalierung min 0 °C max 200 °C

Offsetzeitpunkt 11.05.2005; 13:04 Datum übernehmen; Skalierung min -60 °C max 60 °C

Anzeige Normal; Auswertung Minuten 60 min; Koordinaten Polar

Fig. 6 Temperature profile in the lower regions of a 6-tonne induction furnace for steel near the end of a crucible campaign.

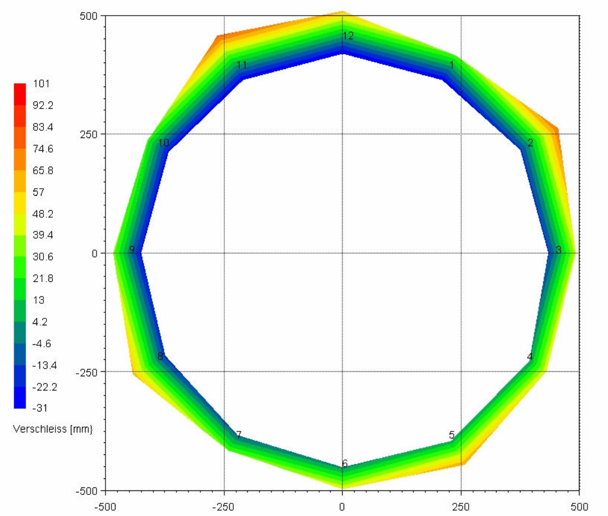


Fig. 7 Result of crucible measurements, showing an integral top-down view of the crucible. Uniform premature wear in the direction of the spout (12 o'clock) and local erosion in the 2, 5, 8 and 11 o'clock positions

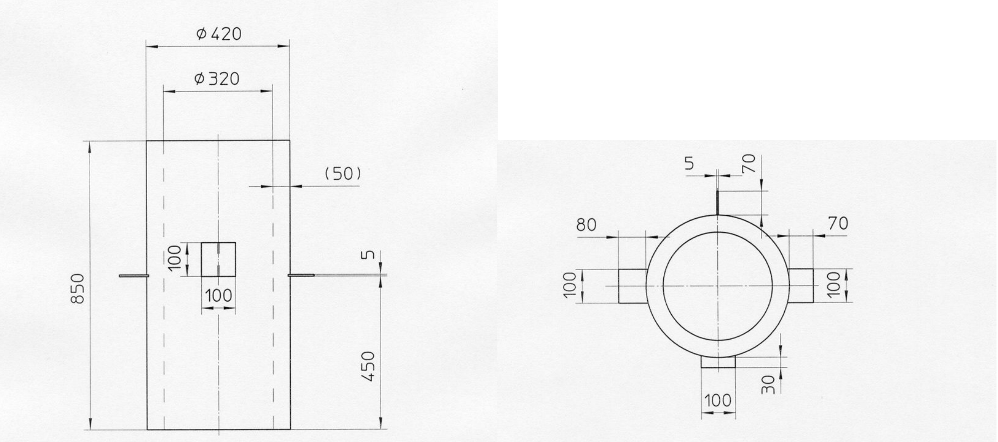
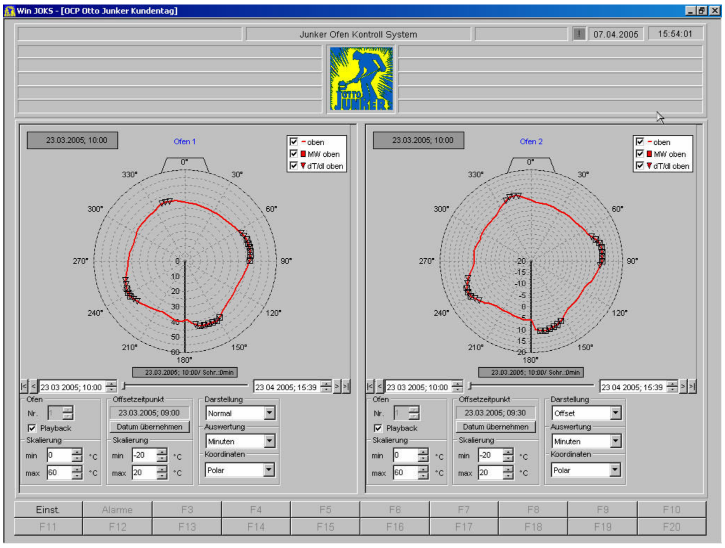


Fig. 8 Thick-walled steel cylinder with welded-on steel plates simulating crucible cracks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23.03.2005; 10:00/ Schr.:0min
23 03 2005; 10:00 — 23 04 2005; 15:39
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Offsetzeitpunkt: 23.03.2005; 09:00
Skalierung: min -20 °C, max 20 °C
Darstellung: Normal
Auswertung: Minuten
Koordinaten: Polar

23.03.2005; 10:00 Ofen 2
23.03.2005; 10:00/ Schr.:0min
23 03 2005; 10:00 — 23 04 2005; 15:39
Ofen: Nr. 1, ☑ Playback
Skalierung: min 0 °C, max 60 °C
Offsetzeitpunkt: 23.03.2005; 09:30
Skalierung: min -20 °C, max 20 °C
Darstellung: Offset
Auswertung: Minuten
Koordinaten: Polar

Fig. 9 Temperature profiles after 30 minutes (10:00 a.m.), with all defects duly reported; absolute temperature (left) and offset display mode (right)