Advances in Contactless Online-Temperature-Measurement with IR-Pyrometry

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IR-pyrometry is a contactless temperature measurement technology with increasingly numerous application areas due to many advantages compared to thermocouples. One of these advantages is the possibility to use fibre optics between the measuring head and the analysis electronics, which allows the spatial separation of sensitive parts from the rough conditions close to the measured object. At IME Process Metallurgy and Metal Recycling, a department and chair of RWTH Aachen University, aluminothermic reduction of TiO_2 is used as a first step for the production of γ-TiAl alloys. The acquisition of the casting temperature of the melt as a basis for continuous quality assurance and an energy balancing system cannot be fulfilled by conventional temperature measurement technology. Therefore, a pyrometer is connected with a standard fibre optic cable and, via a connector, with a 2 m long single fibre quartz fibre optics. The single fibre quartz fibre optics is mounted into the downsprue of the mould in which the alloys are cast. Thus, the melt temperature can be measured during filling of the mould immediately after the reaction end. The experimental results of this application of pyrometer temperature measurement are described in this article and compared with the results of the heat balance calculation.

Keywords:

Infrared pyrometry – Process control – Temperature measurement – Fibre optics – Aluminothermic reduction – Electro slag remelting

Fortschritte bei der berührungslosen Online-Temperaturmessung mittels IR-Pyrometrie

IR-Pyrometrie ist eine berührungslose Messtechnologie, die aufgrund zahlreicher Vorteile gegenüber Thermoelementen zunehmend an Einsatzgebieten gewinnt. Einer davon ist die Möglichkeit zum Einsatz von Lichtleitfasern zwischen Messkopf und Auswertelektronik, die eine räumliche Trennung zwischen empfindlichen Bauteilen und den rauen Umgebungsbedingungen in der Nähe des Messobjekts ermöglicht. Am IME Metallurgische Prozesstechnik und Metallrecycling, Institut und Lehrstuhl der RWTH Aachen, wird die aluminothermische Reduktion von TiO_2 als erster Prozessschritt zur Herstellung von γ-TiAl-Legierungen eingesetzt. Die Erfassung der Schmelzetemperatur beim Abstich, die für die kontinuierliche Qualitätssicherung und zur Verifizierung der thermochemischen Berechnungen anhand einer Wärmebilanz benötigt wird, kann mit konventioneller Thermoelement-Messtechnik nicht durchgeführt werden. Aus diesem Grund wird ein Quotientenpyrometer über ein Standardlichtleitfaserkabel und einen einadrigen Quarzlichtleiter mit dem Einguss der Kokille verbunden, in die die Schmelze abfließt. Durch diese Anordnung kann die Schmelzetemperatur während des Befüllens der Kokille unmittelbar nach dem Reaktionsende gemessen werden. Die experimentellen Ergebnisse dieses Einsatzgebietes pyrometrischer Temperaturmessung werden in dieser Arbeit beschrieben und mit den Ergebnissen der theoretischen Wärmebilanzrechnungen verglichen.

Schlüsselwörter:

Infrarotpyrometrie – Prozessüberwachung – Temperaturmessung – Lichtleitkabel – Aluminothermie – Elektroschlackeumschmelzen

Progrès de la mesure sans contact de la température en ligne par pyrométrie infrarouge

Avances en la medición de la temperatura en línea sin contacto mediante pirometría infrarroja

1 Introduction

IR-pyrometry is a contactless temperature measurement technology with increasingly numerous application areas due to many advantages compared to thermocouples. There is in principle no physical limit for the maximum temperature measured with pyrometric technology, while especially at high temperature processes between 1820 °C and 2315 °C only expensive and brittle tungsten-rhenium-thermocouples can be used. Thermocouples for higher temperatures are not commercially available. Furthermore the response time is extremely short. Actual publications proofed, that acquisition times even in the µs- and ns-range are possible. [1, 2] There is absolutely no back coupling from the pyrometer to the measured object which is of high importance for small samples to avoid a changing of their real temperature by the measurement as well as for high precision alloys, where the contact between thermocouple or thermowell and melt leads to contamination. The fourth main advantage is, that there is no interconnection between electro magnetic fields from vacuum induction furnaces or electric arc furnaces and the measuring head, since only a fibre optics must be close to the measured object and the analysis electronic can be positioned far away. Even nowadays inaccuracy of the measured values is countered very often as disadvantage. It has been shown that this prejudice typically results from use of the wrong pyrometer type and negligence of important parameters like emission coefficients, sensitive spectral bands and atmospheric conditions [3].

2 Fundamentals

Pyrometers are in general divided into two groups. Total radiation pyrometers detect at least 90 % of the total emitted radiation spectrum of the measured object. Since all lenses, filters and detectors must be sensitive in a large area on the one hand and the influence of wave length dependency of the emission coefficient and atmospheric errors on the other hand is rather huge, this kind of pyrometers is nowadays used rarely. The second group, the partial radiation pyrometers, is divided into band radiation pyrometers and spectral pyrometers. Both types are sensitive only in a small range of the total spectrum. While the range of band radiation pyrometers is wider (e.g. 8 to 14 µm), because they are commonly used for organic materials with low wave length dependency of the emission coefficient, spectral pyrometers have a very small sensitive range [3].

The energy which is emitted from a material, can be calculated with the Wien and Planck formula (Equation 1). Because the emission coefficient of real materials is a function of the wave length and the temperature, spectral pyrometers have the advantage, that the difference between λ_0 and λ_1 is rather small. In this case ε can be assumed to be independent from λ and only a function of the temperature. If the emission coefficient of a material is known at the measured temperature, a spectral pyrometer gives very satisfying results.

$$\Delta E = \int_{\lambda_0}^{\lambda_1} \varepsilon \cdot \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{(hc/k\lambda T)} - 1}\, d\lambda \qquad (1)$$

(ΔE: emitted energy [J]; ε: emission coefficient [1]; h: Planck's constant [$6.626 \cdot 10^{-34}$ J s]; c: light velocity [$2.998 \cdot 10^{8}$ m/s]; k: Boltzmann's constant [$1.38 \cdot 10^{-23}$ J/K]; λ: wave length [m/s]; T: temperature [K])

Under working conditions there are several disturbing influences, that make it difficult to predict the emission coefficient. Metallic melts usually are covered with a thin slag skin, for which often no values are available. Deviations in slag composition and slag thickness can change the emission coefficient. Additionally smoke formation during a metallurgical process dampens the transient irradiation and disturbs the signal. Therefore, the measured temperature is often too low.

The problem of the unknown emission coefficient can be solved if following estimation is made. If the emission coefficient is constant in two small ranges of the radiation spectrum, division of the emitted energy in both ranges will eliminate the emission coefficient and produce a stable basis for derivation of the temperature. If smoke formation or other dampening occurs, both ranges are changed similar. Therefore, the temperature measurement is also independent from outer disturbances. Usually the measurement is conducted in two wave length ranges, that are close together. The pyrometers are called 2-colour-pyrometers. Special applications demand even higher accuracy. In this case 3- or 4-colour-pyrometers are used which can compensate specific disturbances of the signal due to thermal stimulation of atoms or molecules or absorption effects of outer atmosphere.

The use of fibre optics between measuring head and analysis electronic allows the spacious separation of sensitive parts from rough conditions close to the measured object. LACHMUND [4] refers about promising experiments for continuous measuring of the temperature inside a steel converter. A fibre optics without lenses is constantly moved into the converter through a bottom valve. The end of the fibre optics is connected with the pyrometer.

3 Application of IR-pyrometry to aluminothermic γ-TiAl-Nb production

3.1 Process design of the aluminothermic γ-TiAl-Nb production

At IME Process Metallurgy and Metal Recycling, department and chair of RWTH Aachen University, following so-called IME-γ-TiAl-Process was designed. TiO_2 which can be brought in as pigment or possibly as high-grade rutile, is mixed with alloying metal oxides (e. g. Nb_2O_5 or Cr_2O_3) and reduced in an aluminothermic reaction. While conventional aluminothermic reactors produce large blocks that must be crushed, melted (typically VIM) and cast into ingots, the IME-γ-TiAl-process fulfils this in a one-step in-line process. Immediately after the end of the aluminothermic reduction the metal is cast into the mould through a bottom tap-hole. Before the reaction, the mould is filled with argon to prevent any nitrogen contamination of the ingot which is the prime-electrode for the further remelting [5-7].

The IME prime-electrode still has a high oxygen content due to the fact, that the reduction ability of aluminium is not high enough to deoxidise titanium to low oxygen contents. Therefore, a remelting step is fulfilled in an inert gas electro slag remelting furnace (IESR). A so-called active CaF_2-Ca-slag can be used as refining agent to reduce the oxygen content. Further a contamination of the metal with nitrogen from small leakages in the furnace as described in [8] for VAR can be avoided if an overpressure is used. Depending on the results of the IESR process and the demands of aviation industry a final VAR step is proceeded to fulfil the certificate requirements.

The requirement of the casting temperature acquisition of the melt as basis for a continuous quality assurance and energy balancing system can't be fulfilled by conventional temperature measurement technology. Due to the very high temperatures and strong reducing environment as well as the mechanical impact from pressure impulses, it is impossible to use thermocouples inside the reactor during the reaction. The mounting of a thermocouple inside the downsprue of the mould would lead to very imprecise results, since the melt cools down significantly within a few seconds and therefore, the response time of thermocouples is not high enough.

3.2 Set up for temperature measurement

The following experiments were conducted with the IR quotient pyrometer QKTR 1485 from the company Dr. Georg Maurer GmbH, Kohlberg, Germany. The response time is 20 ms, the working range is factory-set to 1000 to 3300 °C. The precision is 1 % ± 1 °C and the reproducibility 0.3 %. The sensitive spectral bands lie between 850 to 1100 nm and 950 to 1100 nm, respectively.

As can be seen from Figure 1, the sensitive spectral bands are not influenced from the range of the main spectral lines of the alloying elements titanium, aluminium and niobium and their typical ions. Therefore, a disturbing of the measuring signal due to thermal stimulation of the atoms is not expected. The spectral lines in Figure 1 are presented considering the composition of a Ti-45Al-10Nb-alloy. The data are taken from the National Institute of Standards and Technology, Gaithersburg [9].

The pyrometer is connected with a standard fibre optics type GM-L48 (1.1 mm fibre bundle) and over a connector with a 2 m long single fibre quartz-fibre-optics type 40.11.044 (ø 0.6 mm) from the company Loptek Glasfasertechnik GmbH & Co. KG, Berlin, Germany. The single fibre quartz-fibre-optics is mounted into the downsprue of the mould. Thus, the melt temperature can be measured during filling of the mould immediately after the reaction end. The experimental set up for the temperature measurement with the IR quotient pyrometer is shown in Figure 2.

Since the logging interval of the computer data logging system is 0.5 s which is too high for accurate data acquisition, an additional analogue circuit is used to store the peak signal from the pyrometer. As can be seen in Figure 3 a standard operational amplifier compares the voltage of

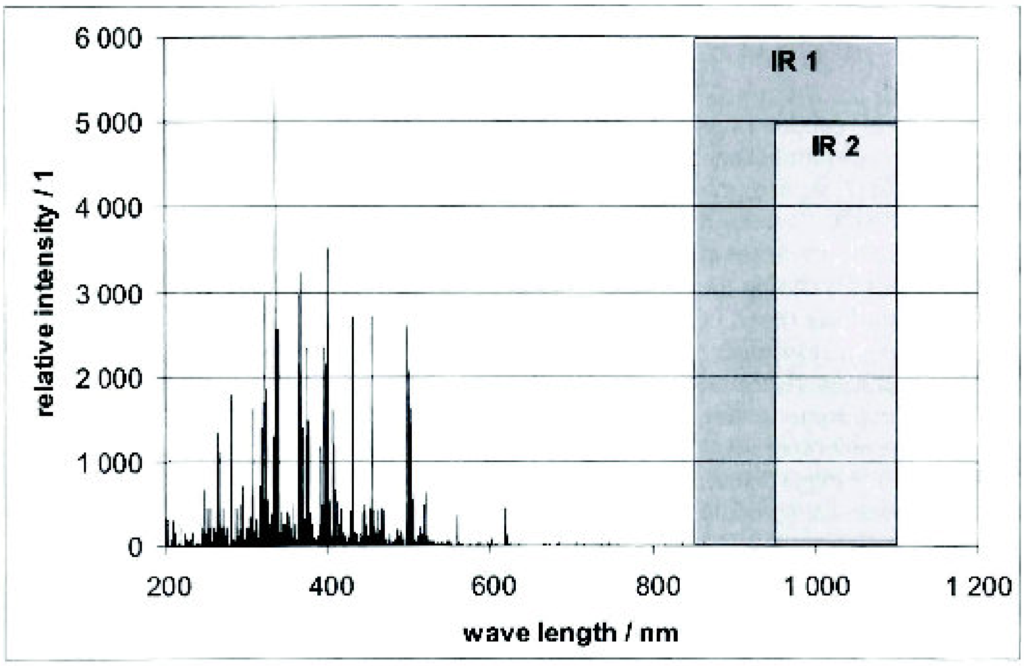


Fig. 1:
Atomic emission spectrum of a Ti-45Al-10Nb-alloy (data: [9]) and sensitive spectral bands of the IR quotient pyrometer QKTR 1485

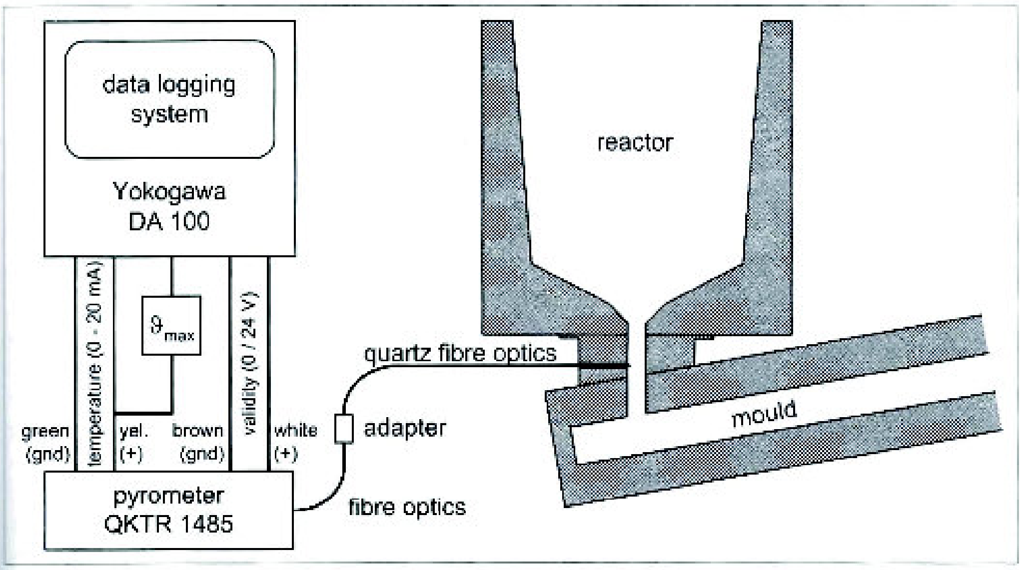


Fig. 2:
Experimental set up for temperature measurement with IR quotient pyrometer

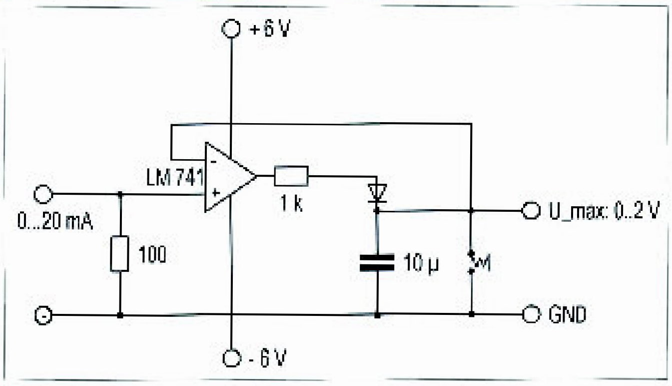


Fig. 3: Analogous peak temperature storage circuit

a capacitor with the output signal from the pyrometer. If the voltage of the capacitor is too low, it is charged. Due to a diode behind the operational amplifier it's impossible to discharge the capacitor, if it's voltage is higher than the signal from the pyrometer. The capacitor must be discharged manually. Tests didn't show a difference between peak voltage and input signal which means, that the correspondence is better than 0.07 %.

3.3 Experimental results

During a first experiment in which the local reaction rates and the progress of the reaction front during aluminothermic γ-TiAl-Nb production were determined [7] the temperature signal showed a very short peak at 1830 °C, decreased to the solid-liquid-range at 1450 °C, stabilized after that at about 1560 °C and finally decreased very slowly during the next 20 minutes to 1000 °C, where the working range of the pyrometer was left (Figure 4). The peak measurement technology was not used during this experiment. Because the additional measuring sensors in this experiment were molten according to plan, the process temperature was estimated to be lower than during ordinary experiments. The amount of molten steel from the sensor housings could be calculated from the metal analysis of the final ingot. The amount of molten lining material from the sensor housings couldn't be evaluated, since it was not possible to investigate, if the lining material was molten before or after the end of the reaction. Because of this and the uncertainty of the temperature signal due to the long acquisition time of the data logging system a second experiment was conducted to collect data for a heat balance of the aluminothermic γ-TiAl-Nb production process.

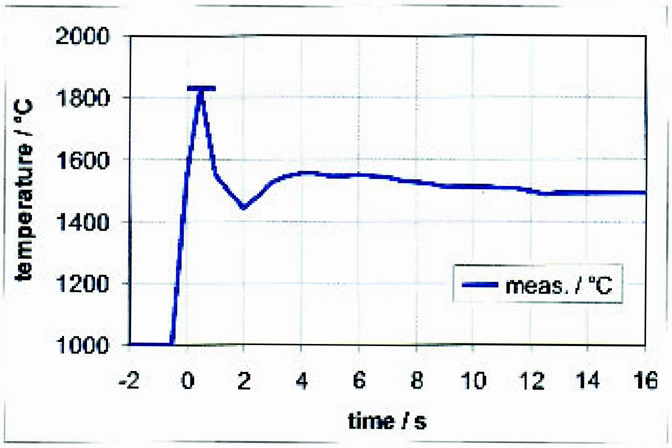


Fig. 4: Run of the temperature during the tapping of the melt (first experiment)

In this experiment a slightly modified alloy was produced. The theoretical adiabatic process temperature was adjusted below the temperature in the first experiment, but because of the missing energy losses from the sensor housings the real process temperature should be higher. As can be seen in Figure 5, there is a short peak at 1920 °C in the peak signal which is about 25 °C higher than the maximum amplitude from the direct measured signal. After a second wider peak at 1900 °C the temperature signal remains in the range of the solid-liquid interval for four seconds and decreases quickly below the working range of the pyrometer.

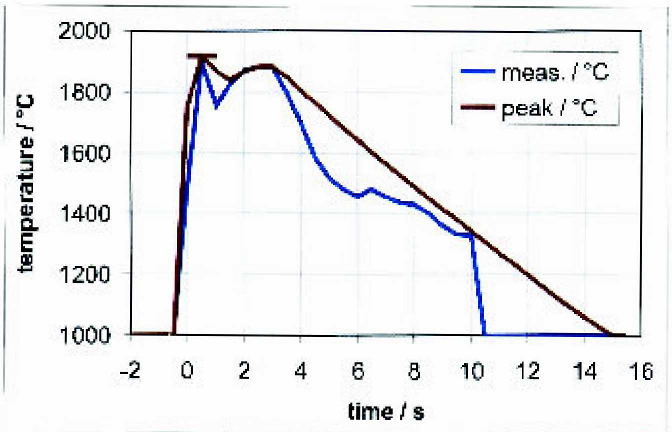


Fig. 5: Run of the temperature during the tapping of the melt (second experiment)

This different behaviour can be explained with the fact, that a small droplet of liquid melt (Figure 6) plugged the aperture in which the fibre optics was positioned. The droplet cooled down rather quickly and concealed the slow cooling metal in the downsprue. In spite of the extreme hot and reducing conditions during the tapping the fibre optics was not damaged as can be seen in Figure 7. An external

Fig. 6: Solidified γ-TiAl-Nb droplet out of the temperature measurement hole

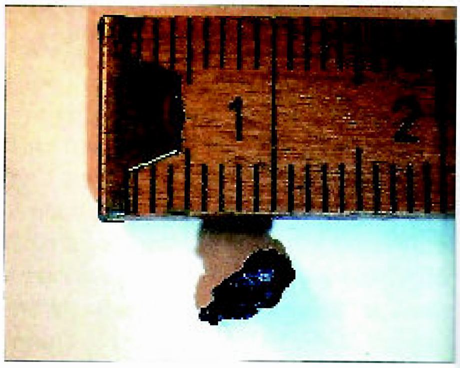
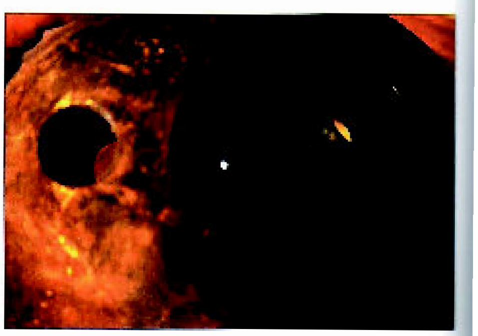


Fig. 7: White spot from an external light source on the surface of the not damaged fibre optics in the aperture after the experiment



light source was connected with the pyrometer side of the fibre optics. The figure shows that the white spot from this source can be seen clearly in the aperture on the mould side of the fibre optics.

3.4 Temperature calculation by heat balancing

All following thermo-chemical calculations were conducted with the Gibbs-energy minimising program FactSage 5.3.1 [10] with following phases and databases:

- gas-phase: FACT 5.3-database, real behaviour,
- liquid-phase: 9329-Al-Nb-Ti-database, TiO and minority-compounds ideally added,
- slag-phase: FToxid-SLAGA, NbO ideally added.

Neither the reaction mixture nor the reactor were preheated before the experiment. Therefore, the temperature of the input materials (totally 185 kg) was assumed to be 25 °C. The theoretical adiabatic process temperature was calculated to be 2008 °C. Beside the potassium chloride which is the main gaseous component, 2.6 kg aluminium evaporate as AlCl, Al_2O and Al. The total amount of produced gas-phase is 213 mol or 4.8 Nm^3.

During the reaction the mixture looses energy by radiation to the outer atmosphere and heat conduction to the reactor lining. The calculation of the energy losses by radiation can be fulfilled, if the progress of the reaction front and herewith the area of the slag surface as measured in [7] is considered. The slag surface can be assumed to be a black radiator due to the hot surrounding mixture and lining material, respectively. From the Stefan Boltzmann's law the emitted power is calculated assuming a surrounding temperature of 150 °C (Figure 8). It can be seen, that in the first 80 % of the total reaction time nearly no energy is emitted due to the first reaction phase in which the reaction burns inside the reaction mixture as described in [7]. Integration of the radiation leads to a total emitted energy of 13.4 MJ.

The energy losses by heat conduction are calculated with a one-dimensional insteady heat transfer simulation described in [11]. The heat transfer coefficient α was assumed to be 5000 W/m²K because of the turbulent conditions in the melt. All other parameters (heat conductivity, heat capacity, etc.) are determined from literature and information from the lining material manufacturer, respectively. The temperature trend in the lining material is shown in Figure 9. It can be seen, that even at a rather long contact duration the impact from the melt to the lining material is rather small. Only a few millimeters of the lining material are significantly heated before the melt is tapped. Therefore, the influence of the heat conduction on the energy balance should be low.

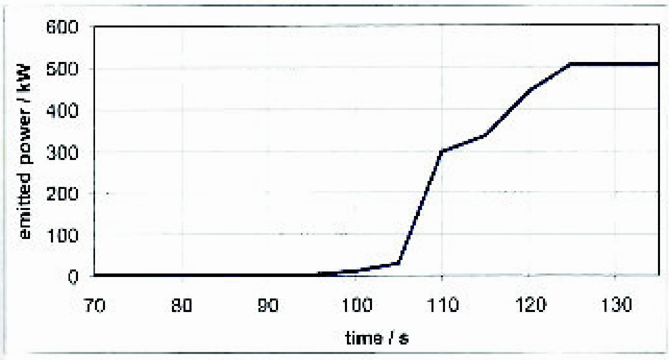


Fig. 8: Emitted power of the reactor as function of the reaction time based on the measurements in [7] and the calculated adiabatic process temperature

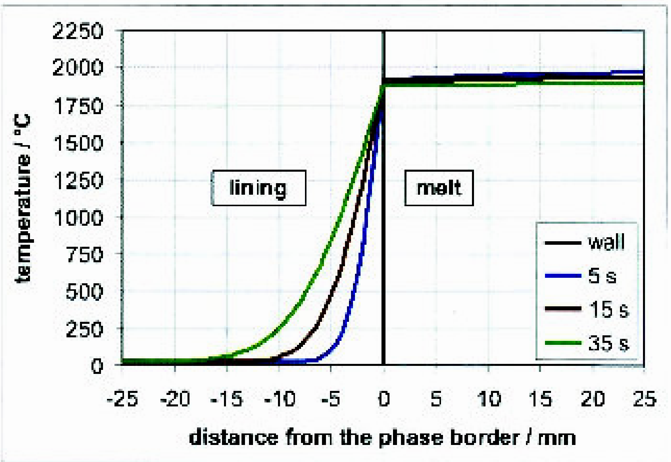


Fig. 9: Emitted power of the reactor as function of the reaction time based on the measurements in [7] and the calculated adiabatic process temperature

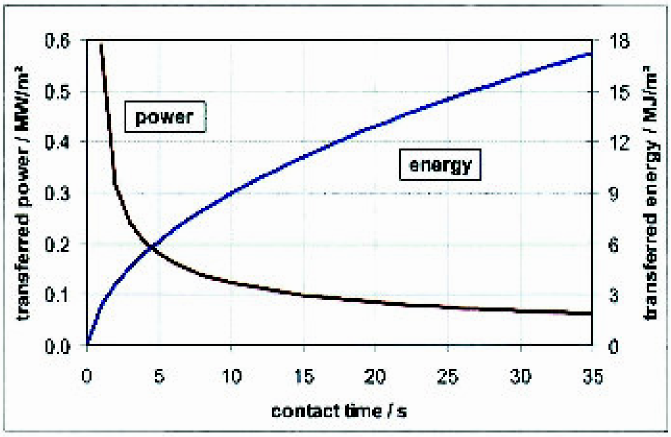


Fig. 10: Calculation of the transferred power and total transferred energy as function of the contact time between melt and lining material

The transferred power and total energy is shown in Figure 10. It can be seen that in the first 10 s of contact time about half of the total energy lost before the tapping is transferred. The calculation of the differential contact area between reactor and melt and the duration of the contact on this area is nearly impossible. Therefore, a rough estimation is done with following assumptions. Before tapping, the total contact area between melt and lining material is 0.63 m². If the average contact time is 15 s, the total amount of transferred energy is 7 MJ. The heat, transferred from melt spillings, must not be considered, since these leave the system border and don't have a significant effect on the remaining melt.

With the calculations from above a heat balance can be set up. The energy is not divided into latent and sensible heat, since this approach is nowadays obsolete. Alternatively the whole balance is calculated with absolute enthalpy values. The total enthalpy of the incoming streams is -1200.61 MJ (Table 1). The enthalpy of the evaporated gas-phase

Tab. 1: Heat balance of the aluminothermic γ-TiAl-Nb production

Input	H [MJ]	Output	H [MJ]
Incoming streams		Evaporated streams	
– Reaction material	-1200.61	– Gas-phase (2008 °C)	1.23
		Condensed streams	
		– Metal phase (1927 °C)	-140.77
		– Slag phase (1927 °C)	-1081.34
		Emitted energy	
		– Radiation	13.36
		– Conduction	7.00
	-1200.61		-1200.52

(1.23 MJ) is rather small compared to the other outputs. The total energy losses due to radiation and conduction are about 20 MJ. Considering this the condensed streams metal and slag must cool down to a final temperature of 1927 °C to adjust the balance. This temperature is in very good agreement with the measured value of 1920 °C.

Summary and outlook

In this work it could be shown that IR-pyrometry is even a suitable method for temperature measuring of very rough processes like aluminothermic reactions. The main advantages are the low response time, high measurable temperatures and the competitive running costs. The precision of the measurements is rather high, if a 2-colour-pyrometer is used which eliminates the disturbances of unknown emission coefficients of the melt and possible smoke formation. An IR 2-colour-pyrometer was connected with a single fibre quartz-fibre-optics, that was mounted into the downsprue of the mould in which the aluminothermic reduced metal was tapped immediately after the end of the reaction. The introduction of an analogous electrical peak measurement circuit allowed an improvement of the peak temperature measurement, since the acquisition time of the data logging system is 0.5 s, while the response time of the pyrometer is 20 ms. A theoretical heat balance was conducted considering the complex thermochemical equilibria between metal, slag and gas-phase and the heat losses by radiation, conduction and evaporated material. The calculated theoretical process temperature of the melt after the end of the reaction goes very well with the measured temperature of the melt during filling of the mould.

Current projects are dedicated to the introduction of the fibre optics based IR pyrometry to other processes. First experiments were conducted in a pressure electro slag remelting furnace under pressures between 0.1 and 4 MPa. They showed that during this process either a continuous cooling of the fibre optics must be conducted to prevent too early melting, or a nozzle must be used to remove the flue dust between fibre optics and melt, since otherwise the temperature of the cooled down flue dust is measured and only short peaks show the surface temperature of the melt. Experiments for measuring the surface temperature during electron beam furnace remelting of titanium are currently prepared.

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