ADVANCED PROCESS MONITORING SYSTEMS FOR CONTINUOUS PROCESSES

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Abstract: The paper deals with a diagnostic and monitoring PC oriented system, based on a unique physical analysis of the process of continuous casting of steel, by utilization of static and dynamic measurements of the monitored process. The basis of the solution is application of an industrial computer with the ability of intranet monitoring of the solidification process in the mould and the strand withdrawal. For the diagnostic purposes, the amplitude of the friction force and the factor of lubrication are evaluated from mould acceleration and mould oscillation mechanism position signals. Friction characteristics and wall temperatures are used for identification of cracks and quality prediction. The automated, PC oriented data acquisition and monitoring system enables prediction of the danger of a breakout that is one of very severe problems in the process of the continuous casting. *Copyright © 2005 IFAC*

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1. INTRODUCTION

Continuous casting process behaviour is determined by simultaneous acting of thermal, mechanical and chemical processes in the casting machine. Knowledge of fluctuating state of the process is a precondition for high quality and defect-free production. The quality depends first of all on the work of the primary and secondary cooling area. Based on numerous research works it can be concluded that it is the mould that has the main influence upon the quality of the blank. Fig. 1 shows a general view on a five-strand billet continuous casting machine.

The casting process technology must meet three basic requirements, i.e. sufficient *production rate,* the specified production *quality* with parallel ensuring of the *safety* against occurrence of breakouts. For the control of the casting process with the aim of meeting the above mentioned requirements it is important to know both thermal and mechanical quantities in the mould.

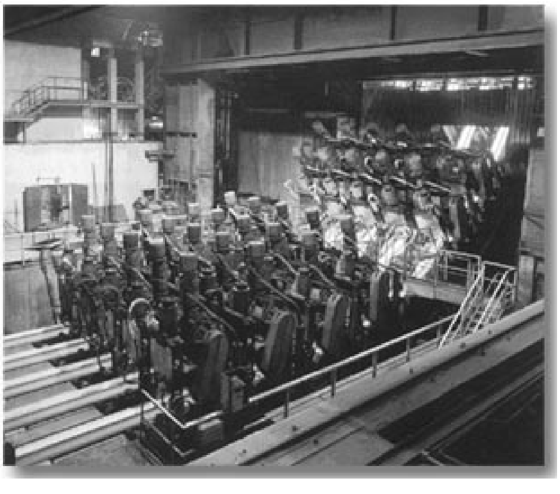


Fig. 1. Continuous casting machine

Knowledge of intensity and uniformity of the heat removal in the mould and the relating shell thickness as well as the forces acting on the blank is required (Pyszko and Cudzik, 2000).

The efforts taken to predict the danger of breakout occurrence and quality control have resulted in a rapid development of continuous monitoring systems. The unique character of each casting machine and variations of heats parameters as well as fluctuation of the casting process itself, however, make it difficult to generalize and require a consistent research activity. The research and development result in a design of intelligent moulds equipped with computer systems for blank quality prediction and breakout elimination.

Two main groups of prediction systems can be distinguished. First there are systems based on methods of mathematical-statistical evaluation of a set of technological parameters. The second approach comes out of continuous monitoring of special quantities measured directly in the mould. It is important to implement additional functions to the system for diagnostics of a caster technical condition, communication with caster control system, instruments for mould dimension and wear measuring and eventually instruments for the technological axis setting. A new system based on the second approach has been developed and it is already in operation. Its main functions and principles are described below.

2. MONITORING AND DIAGNOSTIC SYSTEM DGS

The system DGS algorithms are based on two principles complementing each other, namely measuring and analysis of temperatures in the mould walls and the friction between the strand and the mould. The friction is measured by an indirect method from the mould acceleration and an oscillation mechanism shaft rotation. This is an original indirect measuring method and it is one of the details, which distinguishes the system DGS from other monitoring systems for continuous casting. Other quantities, e.g. cooling water temperature and flow rate are used for the heat removal calculations. A schematic chart of the diagnostics system instrumentation is shown in the Fig. 2

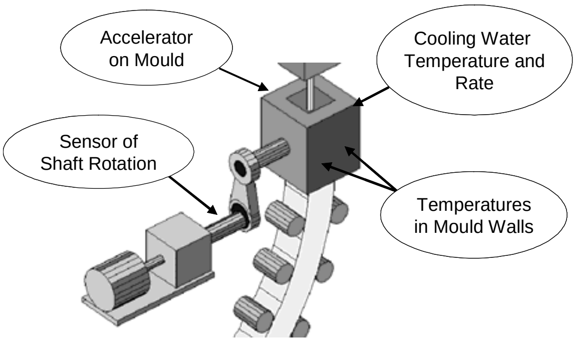


Fig. 2. Diagnostics system instrumentation

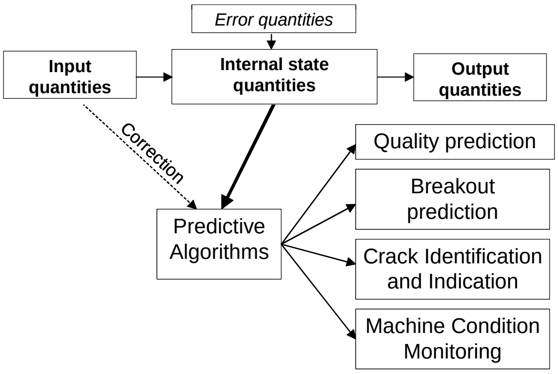


Fig. 3. DGS predictive system block diagram

The system DGS predictive algorithms evaluate mainly the internal quantities measured directly in the mould. Casting machine input quantities (e.g. steel grade, steel temperature, casting speed) are used for correction of the predictive algorithms and for setting of danger alarm limits, see Fig. 3.

The basic functions of the system are the following

- strand quality prediction,
- indication of shell cracks and breakout prediction.

Besides the above-mentioned basic functions, the system features additional functions including

- diagnostics of mechanical conditions of the oscillation mechanism,
- measuring the cooling symmetry on the principle of thermal axis evaluation,
- measuring the heat flow and specific heat removed from steel to the cooling water,
- calculation of the average shell thickness

The analysis of measured values (Fojtik, *et al.*, 2000; Pyszko and Cudzik, 2000) can be further used for other purposes such as comparison of lubrication properties of casting powders, comparison of thermal resistance of lubrication layer, checking of casting powder dosing uniformity, checking of the mould technological axis adjustment and of a proper position of the submerged entry nozzle outlet (SEN).

The system solution is based on industrial computers (IPC). The monitoring and diagnostic system enables process data acquisition by means of analog I/O modules and advanced monitoring and prediction software. Industrial PCs are connected into the intranet to enable realization of a monitoring and early warning system (Vrba, *et al.*, 2001). Both real time and archive data are accessible from any authorized computer connected to the intranet and can be visualised by a special application sharing measured data from a server. An extension of IPC system solution by use of embedded web server will reflect the recent development in industrial use of modern IT and enables process monitoring from arbitrary computer in the framework of the company intranet (Fiedler and Zezulka, 2003).

The diagnostic system DGS has been developed in the company DASFOS, v.o.s. in the Czech Republic in co-operation with VSB - Technical University Ostrava, steelworks Zeleziarne Podbrezova, a.s., Slovak Republic, and Trinecke zelezarny, a.s., Czech

Republic. At present it is in operation at both billet and block continuous casters on moulds of rectangular and round formats, in the concrete on round moulds with diameter ∅ 320 to 550 mm in Trinecke zelezarny, a.s. and on rectangular moulds with dimensions from 150 to 225 mm in the company Zeleziarne Podbrezova, a.s..

2.1. Diagnostics on the principle of mould friction measurement

Measuring of friction in the mould is desirable for the purpose of casting process control. Friction in the mould creates conditions for development of cracks in the shell. The crack is a consequence of high friction. Also a reciprocal mechanism has been observed in round moulds. In some cases an increase of friction occurs as a consequence of an existing crack that has appeared due to unspecified reason. This is a significant advantage of the system DGS in comparison to other systems that enables an existing crack indication from both temperature and friction changes.

It was proved to be advantageous to evaluate the friction in the mould from two points of view, i.e. according to friction force *amplitude* and friction *character* (the time course). Two basic theoretical models of friction are well known – the dry sliding friction and the linear fluid friction.

The amplitude of the sliding friction does not depend on the relative velocity of the friction surfaces, but depends on direction of movement and on the normal force value. On the contrary, there is a linear dependence of the linear fluid friction on the relative velocity of surfaces and the damping coefficient. The damping coefficient depends on dynamic viscosity of the lubricant, thickness of lubricating layer and an area of friction surfaces. The sliding stress resulting from the friction in the lubricant layer is given by product of the lubricant dynamic viscosity and the velocity gradient in the lubricant (Pyszko, *et al.*, 1999).

Fig. 4 shows the theoretical curve of the friction force in the following cases: a) 100% sliding friction, b) 50% sliding and 50% fluid friction, and c) 100% fluid friction. The fluid friction is characteristic by lower amplitude during the negative strip time in comparison with the sliding friction.

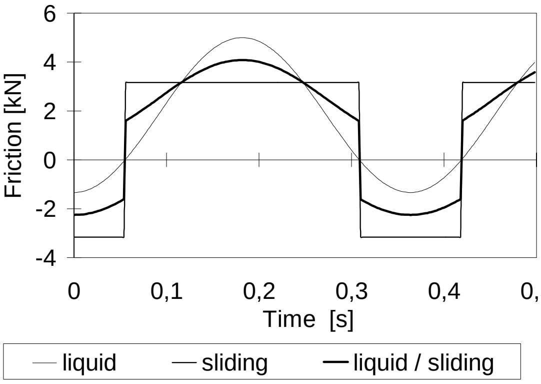


Fig. 4. The theoretical curves of the friction force

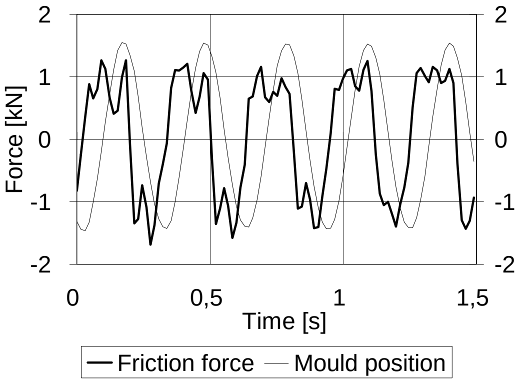


Fig. 5. Actual friction force in a real mould

The friction character is evaluated as a ratio of the sliding and the fluid components. The sliding friction is characterized by step changes of the friction force in the nodal points, i.e. in the moments of stripping direction change, while the linear fluid friction changes fluently without impacts.

In the real mould there is non-linear liquid friction developing due to „non-Newton's“ behaviour of the lubricant. It means that the lubricant viscosity is not constant but it depends on the sliding stress in the lubricant layer and varies significantly with the temperature. The step changes of the friction force caused by sliding friction generate a dynamic stress in the shell and consequently a crack danger. It is well known that an impact character of load results in earlier tearing of the shell than in case of steady or fluently changing load. At the same time, the non-linearity in the friction force incites undesirable vibrations of the mould causing negative influence both on the oscillation mechanism and the shell.

Fig. 5 shows the real friction force analyzed from a dynamometer signal measured at an experimental mould. Remarkable oscillations are caused by the sliding friction component. In an ideal case when the surfaces are perfectly lubricated, the friction force is proportional to the relative velocity of surfaces, and in turn, it damps the undesirable vibrations of the mould. The friction character is evaluated by the DGS system using the principle of the mould vibrations frequency analysis.

The amplitude of the total friction force in case of the system DGS is measured by an indirect method based on dynamic analysis of the oscillation mechanism position and mould acceleration signals. The amplitude and proportions of the sliding and fluid components of friction in the mould are evaluated. Previous research showed that the friction depends primarily on technological casting parameters such as casting speed, oscillation frequency and amplitude, steel grade, casting powder, etc (Pyszko and Cudzik, 2000). The continuous casting process is variable and dynamic. Even under constant casting parameters there are friction changes detected by the monitoring system.

The DGS system determines the amplitude and the character of the friction force in the form of relative non-dimensional quantities called "friction factor" (a value proportional to the total friction force amplitude) and “lubrication factor” (fluid friction component proportion). Evaluation of both liquid and sliding components of friction measured by the original indirect method is characteristic for the system DGS and makes it more advanced in comparison with other similar systems.

2.2. *Quality prediction based on measurement of temperatures in the mould walls*

In order to achieve a high-quality product it is desirable that the temperatures in the casting shell are *uniform* and report *minimal fluctuations* in time. The temperature changes in the shell relate to the temperatures in mould walls, which are measured continuously. Blank quality prediction is based on their evaluation from the following points of view:

- thermal symmetry – uniformity of a mould thermal field in a horizontal cross-section,
- temperature fluctuations – uniformity of mould temperatures in time.

From 8 to 30 thermocouples, according to the mould format, are installed in the mould wall along the mould perimeter at a single horizontal level, Fig. 6. The signals are amplified, filtered and processed by statistical functions and frequency analysis. The mean value, trend and other statistical characteristics are used for quality and breakout prediction (Prihoda, *et al.,* 1998).

As a temperature field in the mould relates closely to the heat flux, the shell thickness uniformity can be predicted too. Non-symmetrical heat removal in a transversal direction and excessive temperature fluctuations result in a mechanical stress in the casting shell. When the critical values are exceeded, cracks develop.

Non-uniformity of the thermal field and excessive temperature fluctuations may signalize also the casting powder poor lubrication capabilities, insufficient lubricant supplying or defects such as casting powder nests or fused-in frames on the blank surface. The wrong temperature symmetry in a transversal direction may also result from non-uniform cooling water flow, improperly adjusted geometry, wrong position of the SEN or non-symmetrical casting powder dosing.

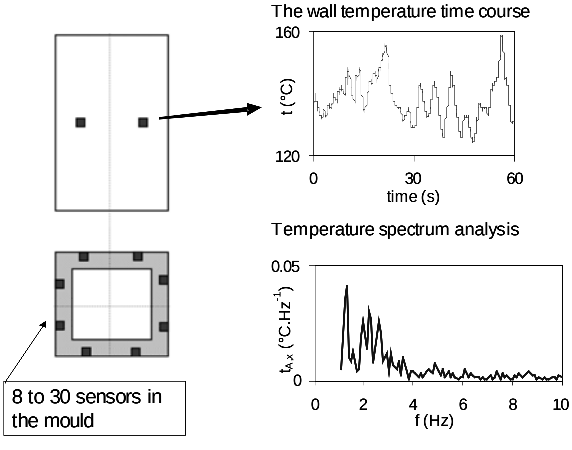


Fig. 6. Installation of temperature sensors

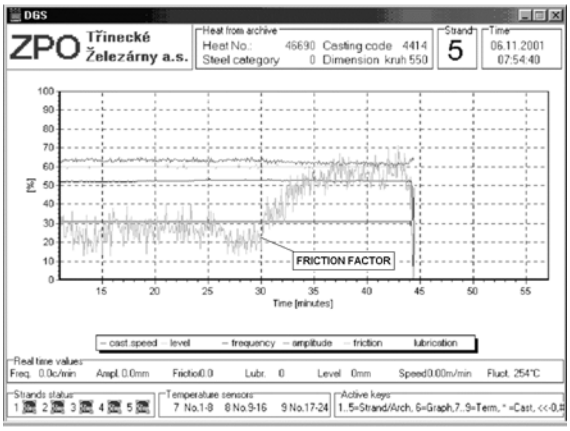
The system judges mould thermal symmetry by means of thermal axis position, which expresses distribution of heat removal around the mould circumference. By evaluation of the average position of the thermal axis it is possible to correct the adjustment of the caster geometry, e.g. misalignment of the mould. For this, however, the preconditions for uniform distribution of the cooling water rate in the mould and proper position of the SEN must be met primarily. The idea of the thermal axis and the algorithm is an original feature of the system DGS.

2.3. *Crack indication and breakout prediction*

The DGS system uses a single horizontal row of temperature probes to indicate cracks in the casting shell. This makes the installation of sensors easier and cheaper in comparison with other existing systems, which use two layers of thermocouples. Sensor maintenance costs were reduced too. On the other hand this solution required development of more advanced prediction algorithm in comparison with other systems. The DGS system uses the algorithm which, apart from the values and trends of wall temperatures, evaluates dislocation of the thermal axis as well as the amplitude and character of friction in the mould to increase the breakout prediction reliability and reduce the number of false alarms. Especially the breakout prediction executed from both temperature signals and friction contradistinguishes the system DGS from other existing systems. This principal brings advantages in particular during casting round strands.

A crack causes decreasing of the shell thermal resistance and the measured temperature in the mould wall rises near the crack. In addition in some cases, the friction and lubrication factors change. The system decides automatically on the activation of the alarm. The response to the alarm must be as quick as possible as the time in which the crack achieves the mould lower edge varies between 10 to 30 seconds according to the casting speed. Both the moment of the alarm and the time of operator’s response are recorded in the file for later analyses.

Fig. 7 indicates the progress of the friction factor prior to the breakout. It relates to the real casting of a round blank ∅ 550 mm.



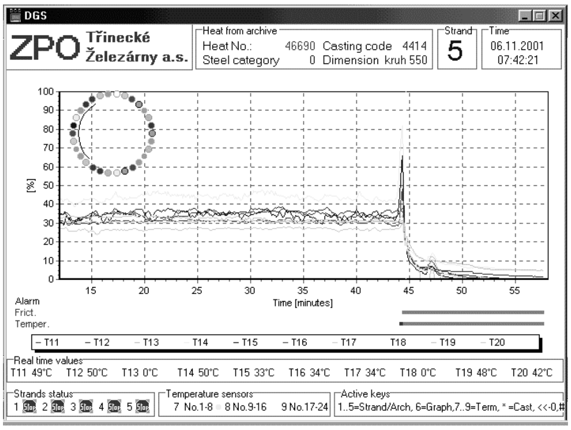
Heat from archive
Heat No.: 46690 Casting code 4414
Steel category 0 Dimension kruh 550
Strand 5
Time 06.11.2001 07:54:40

Real time values
Freq. 0.0c/min Ampl. 0.0mm Frictio0.0 Lubr. 0 Level 0mm Speed0.00m/min Fluct. 254°C

Temperature sensors
7 No.1-8 8 No.9-16 9 No.17-24

1..5=Strand/Arch, 6=Graph,7..9=Term., * =Cast, <<-0,#

Fig. 7. The rise of the friction factor prior to the breakout



Heat from archive
Heat No.: 46690 Casting code 4414
Steel category 0 Dimension kruh 550
Strand 5
Time 06.11.2001 07:42:21

Real time values
T11 49°C T12 50°C T13 0°C T14 50°C T15 33°C T16 34°C T17 34°C T18 0°C T19 48°C T20 42°C

Strands status
1 Stop 2 Stop 3 Stop 4 Stop 5 Stop

Temperature sensors
7 No.1-8 8 No.9-16 9 No.17-24

Active keys
1..5=Strand/Arch, 6=Graph,7..9=Term, * =Cast, <<-0,#

Fig. 8. Temperature response in the mould wall before the breakout

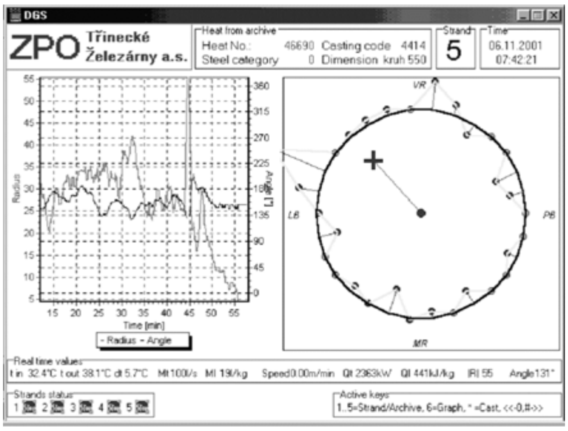
Friction increase starts about 15 minutes prior to the breakout, thus creating conditions for breakout. The breakout occurred in 44th minute of the record. The event occurred during the DGS system testing when the operator was not able to response to the alarm message of the system. The signals of the temperature sensors during the same heat are shown in the Fig. 8. The temperature rise on the sensors resulted in the alarm report just before the breakout.

By contrast to other similar systems which evaluate differences between signals from neighbouring thermocouples in vertical direction, the DGS algorithm of the crack indication and breakout prediction evaluates temperature increase and differences between signals from neighbour temperature probes in horizontal layer as well as the thermal axis position.

The crack usually does not come into existence in a symmetric way, but it is initiated in a certain place and gradually spreads to the sides. From this reason the temperature growths on each temperature probe are shifted in time and the signals report significant temperature differences for a certain period of time. The crack is therefore manifested by a sudden disturbance of the thermal field symmetry.

Fig. 9 shows the DGS system screen during the same heat as in the previous figure. The diagram on the left side of the screen shows the course of polar co-ordinates of the thermal axis. The cross in the right section of the screen indicates the current position of the thermal axis. About 20 seconds before the breakout a significant shift of the thermal axis was observed.

Fig. 10. shows the courses of casting speed, friction factor and other quantities during another casting, when a danger of breakout appeared. Two alarms evaluated by the algorithm based on the friction increase were reported in the 21st and 23rd minute. The experienced operator responded by reducing the casting speed even before the alarm signal based on monitoring the growing friction factor. After the alarm messages the casting speed was reduced even more. After 15 minutes the friction started dropping and operator was gradually increasing the casting speed up to the original value. Increasing of friction was a consequence of strand cracking.



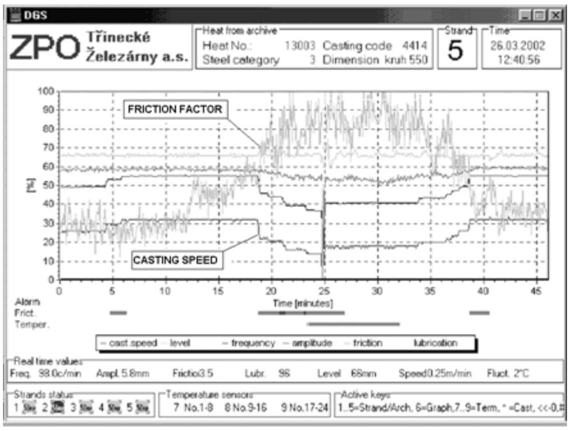
Heat from archive
Heat No.: 46690 Casting code 4414
Steel category 0 Dimension kruh 550
Strand 5
Time 06.11.2001 07:42:21

Real time values
t in 32.4°C t out 38.1°C dt 5.7°C Mt 100l/s Ml 19l/kg Speed 0.00m/min Qt 2363kW Ql 441kJ/kg |R| 55 Angle 131°

Strands status
1 2 3 4 5

Active keys
1..5=Strand/Archive, 6=Graph, * =Cast, <<-0,#->>

Fig. 9. The thermal axis and temperature symmetry screen



Heat from archive
Heat No.: 13003 Casting code 4414
Steel category 3 Dimension kruh 550
Strand 5
Time 26.03.2002 12:40:56

Real time values
Freq. 98.0c/min Ampl. 5.8mm Frictio 3.5 Lubr. 96 Level 66mm Speed 0.25m/min Fluct. 2°C

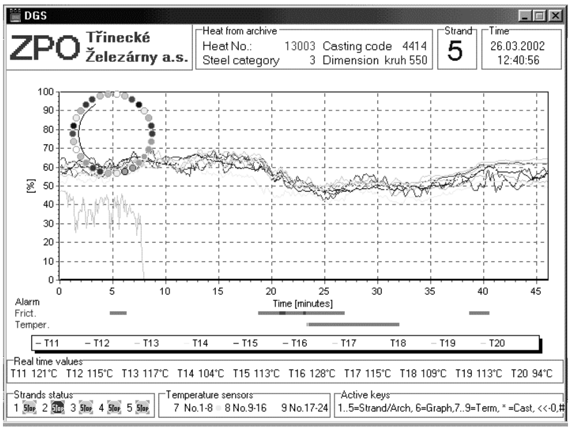
Strands status
1 Stop 2 Stop 3 Stop 4 Stop 5 Stop

Temperature sensors
7 No.1-8 8 No.9-16 9 No.17-24

Active keys
1..5=Strand/Arch, 6=Graph,7..9=Term, * =Cast, <<-0,#

Fig. 10. The main screen of the DGS system during breakout danger

It is obvious from the Fig. 11., that the danger of breakout in this case did not show on the temperature sensors. The temporary drop of temperatures was caused by decrease in casting speed. The breakout prediction in this case was based on friction only. It was the case of a narrow longitudinal crack, where temperature rise at sensors was be under the ordinary temperature fluctuations. A longitudinal crack, however, showed quite reliably in growth of the friction factor. The integration of algorithms for breakout prediction both from temperatures and from friction brings higher probability of successful prediction of longitudinal crack during casting round blanks.



Heat from archive
Heat No.: 13003 Casting code 4414
Steel category 3 Dimension kruh 550
Strand 5
Time 26.03.2002 12:40:56

Real time values
T11 121°C T12 115°C T13 117°C T14 104°C T15 113°C T16 128°C T17 115°C T18 109°C T19 113°C T20 94°C

Strands status
1 Stop 2 Stop 3 Stop 4 Stop 5 Stop

Temperature sensors
7 No.1-8 8 No.9-16 9 No.17-24

Active keys
1..5=Strand/Arch, 6=Graph,7..9=Term, * =Cast, <<-0,#

Fig. 11. Mould temperatures during the heat with a danger of breakout

4. CONCLUSIONS

The continuous monitoring of the working conditions in the continuous casting mould uses a principle of diagnostics by measuring special quantities directly in the mould.

The DGS monitoring and diagnostic system is based on industrial computers. These are connected to the intranet to enable realization of a monitoring and early warning system.

The system DGS features several original principles and functions which make it more advanced in comparison to other systems.

The DGS system simultaneously executes measurement both of friction in the mould and wall temperatures. The friction is assessed from two points of view, namely amplitude of the friction force (so-called friction factor) and proportion of fluid friction component (lubrication factor). Based on the measured parameters of friction, temperature fluctuations and temperature field symmetry in the mould, it is possible to forecast the quality of the blank and breakout.

Both real time and archive data can be visualised by a special application at any authorised computer connected to the company network. To enable process monitoring from any computer inside the company intranet by web application, a recent extension of the DGS system, using an embedded web server to meet increasing demands on supervision functionality is planned.

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