RESEARCH OF HEAT TRANSPORT IN MOULD FOR CONTINUOUS CASTING OF STEEL

This report describes research of thermal processes in primary cooling area in terms of assessment of temperature profiles and determination of thermal flows of the mould. Even formation of casting crust in mould depends on its thermal work, related to distribution of temperature along the height of individual mould walls, which affects operation of the whole continuous casting machine (CCM) in fundamental way. Ideal temperature profile along the height of the mould assures even removal of heat from a blank and it is an essential prerequisite of high quality production. A separate part has been dedicated to ways of preventing breakouts with the use of simulation of kinetics of the mould temperature field. Some of the achieved results are shown on particular examples.

Key words: continuous casting of steel, mould, heat removal

Ispitivanje prijenosa topline u kalupu za kontinuirano lijevanje čelika. Rad prikazuje istraživanje temperaturnih profila i određivanje toplinskih tijekova unutar kalupa u primarnoj zoni hlađenja. Jednolikost stvaranja ljevačke kore u kalupu ovisi o njegovom toplinskom radu, koji je uvjetovan raspodjelom temperature po visini stijenki konkretnog kalupa, što temeljno utječe na aktivnost cijele opreme za kontinuirano lijevanje. Idealan temperaturni profil duž visine stijenke kalupa jamči jednoliko odvođenje topline s površine i nužan je preduvjet kvalitatne proizvodnje. Posebno poglavlje rada obrađuje prevencije površinskog kidanja materijala koristeći kinetičku simulaciju u temperaturnom polju kalupa. Neki rezultati prikazani su na konkretnim primjerima.

Ključne riječi: kontinuirano lijevanje čelika, kalup, odvođenje topline

INTRODUCTION

The continuous casting technology is characterized by wide multiformity and it is a result of the whole previous stage of preparation of steel production and processing just before the continuous casting process. This complicated and many-condition-dependent process running in mould can be better analyzed and then assessed provided that variables, which change during the casting process, are measured directly in the mould.

One of the ways, how to influence quality of the blank, is to monitor thermal work of the mould during casting. For each mould there is correlation between the thermal flow, which is removed from solidifying steel to cooling water, and temperature of the mould copper wall. From the temperature profile along the wall height or circumference it can be deduced, how tight is the contact between the blank surface and the mould wall and thus what intensity and evenness of heat removal is in the place in question.

Distribution of temperatures, or thermal flows respectively, along the mould height and circumference closely relates not only to the blank quality but also to

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the wear and tear of working surface of the copper wall and foot rollers. The heat removal should be, as far as possible, constant in the mould location and even along the circumference of cross-section. Variable removal of heat induces tension within skin and when critical values are exceeded, cracks occur, which may even result in a breakout.

ASSESSMENT OF MOULD THERMAL WORK

Transport of heat to the mould walls directly results in formation of skin on the solidifying blank. Skin growth is affected by both the internal heat transfer within steel as well as by external sharing of heat on the blank – mould boundary. When the mould is in close contact with steel, the skin growth in the mould upper part is limited by internal sharing of heat, i.e. besides heat convection in molten metal also by the coefficient of heat conductivity, which is a given value for particular brand of steel. External transfer of heat determines the solidification process in the lower part of the mould, in which a gap occurs between the blank and the mould due to thermal contraction of the solidifying steel. Retraction of the skin from the mould wall will substan-

tially impair removal of heat from the steel and the skin growth will slow down. In extreme cases, re-heating of the solidified surface layer of the blank may even occur.

Removal of heat from the mould also depends on carbon content in steel. This especially concerns the peritectic steels, which show larger shrinkage at solidification than the steels with higher carbon content. Thickness of the skin can be increased for these types of steel by casting with lower casting speeds, which, however, is not convenient for a high-capacity casting machine. Another way is to adapt mould taper in critical areas to the peritectic steel shrinkage character. The effort to reach superior contact between the steel and the mould copper wall, and thus to increase the amount of heat removed from the blank, leads to more detailed research of thermal work of moulds [1-4].

Temperature profiles along the height of mould

Monitoring of the mould thermal work can be simplified with the use of the measured limiting conditions to monitoring of temperature fields, as temperatures in the given point of the mould depend virtually linearly on density of the heat flow from the blank. Required presumption is to keep cooling water constant temperature and flow rate [5].

Cast heats have different steel chemical compositions and thus also different shrinkage and formation of the skin. To reach the ideal condition, a different optimal profile of the mould should be used for each steel brand. However, this procedure is not technically feasible due to high production costs of the mould and different operational parameters (casting speed, oscillation frequency, casting powder, casting temperature etc.). Therefore, it is necessary to find such mould profile, which would conform to the most often cast steel brands as much as possible.

From the temperature profiles, it is possible to assess correctness of selected tapers of the mould for the used parameters of casting and the given steel type. To measure particular temperature values in the mould wall, an original methodology of measuring by jacketed thermocouples has been developed, which can measure temperature in any point on the mould. Hot junctions are located on selected places on the mould and signal is led to analogue inputs of the PC measurement card. The thermocouples are located along the height of the mould on the large radius (LR) and small radius (SR) sides. To get ideal contact between the thermocouples and the mould wall, a method of incorporating the thermocouples into copper rolls, which were installed into holes, drilled in the mould wall, was selected.

It is also possible to deduce from the temperature profiles, whether the blank solidification process proceeds in compliance with theoretical assumptions of the
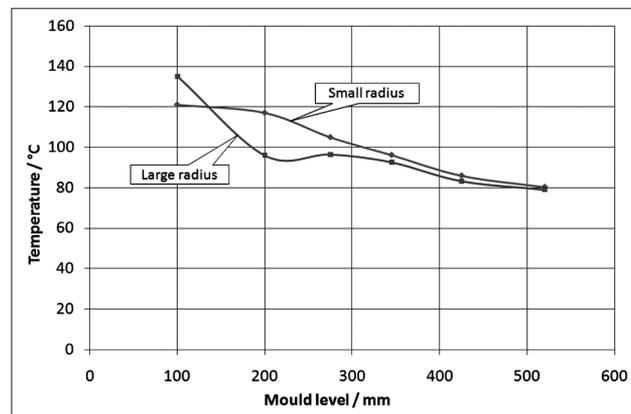

Figure 1. Temperature profile of mould

skin formation in three areas of the mould. These are the upper part of the mould, when the heat transfer is performed from molten steel via the mould wall to cooling water, central transition area and lower area of the mould with already permanent gap between the steel and the mould.

Shapes of the curves for both the radii are usually different and they differ according to chemical composition of the cast steel. An example of a measured temperature profile for a block CCM on both sides of a radius is shown on Figure 1. The temperatures were measured 3 mm under working surface of the mould for the group of low-carbon heats with approximately 0,18 weight % C. The mould for casting of $\varnothing$ 410 mm ring blocks was 600 mm long. It is obvious from the illustration that the temperature profile indicates three typical cooling zones on the LR side. On the SR side the temperatures waveform is even along the whole height of the mould. Different temperature profiles relate to skin growth, gas gap creation and temperature axis orientation.

Heat flows in mould

Removal of heat from the blank in mould substantially affects quality of cast steel and so it is an important indicator of continuous casting. Heat flows in the given point of the mould should be as constant as possible and as even as possible along the circumference of the cross-section. In terms of quality is therefore desirable that temperature changes in skin show minimum fluctuations.

Even and sufficiently strong skin outgoing from the mould should resist ferrostatical pressure and pulling forces of push benches. Also the carbon content in steel significantly affects evenness of heat removal from the mould. Thickness of skin on steel can be increased either by casting with lower casting speeds, or by increasing the heat removed from the mould.

To calculate thermal flows a similar method as for the temperature profiles was selected (direct measurement of temperatures in the mould wall). Pairs of thermocouples for temperature gradient measurement
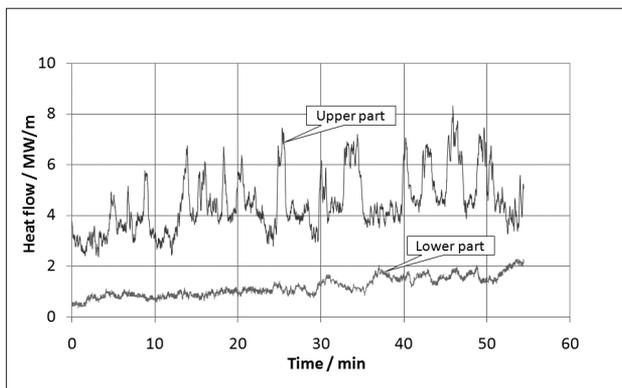
Figure 2. Behaviour of heat flows

were located in the upper and lower parts of the mould on the large radius and small radius sides. Using these gradients, it is possible to simply calculate values of thermal flows in the given point of the mould from the known distance between both thermocouples and heat conductivity coefficient of the mould.

Figure 2 shows calculated heat flows for low-carbon steel on the SR side. Real waveform shows impact of mould oscillation frequency, casting powder quality, actual position of the steel level and other operational reasons. Distinctively pulsating waveform of thermal flows in the upper part of the mould, where no stable skin has been formed yet, is characteristic for the curves. Average value of the heat flow reaches 4,4 MW/m, while in lower part of the mould the heat flows are already more stable and their average value is 1,2 MW/m.

Modelling of kinetics of the mould temperature field

Using the simulation of kinetics of the mould wall temperature field, another part of the research tried to find out, whether occurrence of cracks may influence distribution of temperatures in the mould and whether it is possible to detect real danger of breakout with the use of temperature probes. The subject of the research was determination of suitable position of a probe in both transversal and longitudinal direction with reference to the type of cracks occurring most often. Time of temperature probe response to jump growth of the heat flow on the mould internal wall has been also theoretically researched. To solve the problem in question, a network otherwise differential method was used.

Accuracy of the numerical solution is given especially by fineness of the given area dividing, i.e. by a linear step of the network. With the decreasing distance between nodal points the accuracy increases, however, on the other side, the number of operations and thus also time of solution on PC increase. For the given conditions of uniqueness there is certain optimal discretization, when the solution accuracy is sufficient and the time of calculation is still bearable. Earlier research works Š6Ć have proven that for numerical calcu-

lations of the temperature field of the copper mould it is optimal to select the distance between the network nodal points in the direction perpendicular to surface of the blank approximately 1 mm and 5 mm in horizontal direction.

The program allows the simulated crack to be positioned anywhere along the width of the mould. The crack has been modeled by the impact of increased heat flow density (q) in two adjacent nodal points. The fig. 3 shows, how high the q value has to be, to make the temperature change in the wall, located 6 mm under the internal surface, clearly identifiable by a thermocouple.

The probe reacts to a crack virtually immediately; the delay is 0,02 s only. Temperature measured by a thermocouple, depending on the heat flow density, would change by 9 K to 32 K within 5 s. In doing so, it applies that a temperature change is more distinctive than a change in density of the heat flow. While the ratio of the largest to the smallest put-down q value is 2,5, the ratio of the corresponding growths of temperatures is 3,48. When assessing these and other solution results (not shown here), it was found out that the q values higher than 1,5 MW/m^2 are the most suitable to be used for cracks modelling.
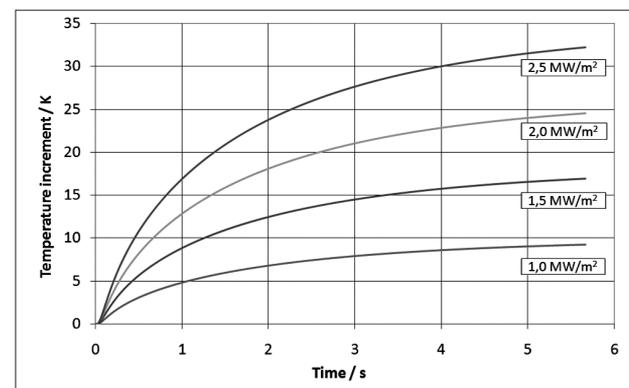

Figure 3. Influence of heat flow density on thermoprobe response in cracks

It should be noted regarding the above described mathematic model, that the blank together with the crack are moving, but the assembled simulation program does not consider this movement. The mentioned conclusions are therefore real only in small time intervals (in seconds). However, when applying the found dependencies in operational conditions, it is not possible to work with times longer than 10 s. If we consider the time required to form the continuous skin and the mould length itself, in which a crack may occur first, then it is obvious, that indication of a crack as late as after 10 s after the crack occurrence has no importance from the practical point of view. The defective area zone is already on the lower level of the mould (or even below it) and thus the casting speed decrease cannot prevent any breakout.

CONCLUSION

Mould thermal work was assessed on operational equipment for steel blank continuous casting on the basis of experimental research. Evaluation was focused on determination of optimal temperature profiles of the mould wall and suitable heat removal in the primary cooling area.

The results reached confirm important impact of chemical composition on waveform of temperature profiles of the mould wall. Also other indicators should be taken into account. This especially concerns the blank position in the casting machine, which is usually not identical with the technologic axis of CCM. During casting the blank moves to individual sides of the mould, while the movement shows frequency in order of tens of seconds to tens of minutes. This phenomenon causes asymmetrical cooling of the blank, especially in the lower part of the mould.

Waveform of thermal flows shows influences of mould oscillation frequency, casting powder quality, actual position of the steel level and other operational reasons. The upper part of the mould is characterized by distinctively pulsating waveform of thermal flows, as no stable skin has been formed here yet.

When simulating impact of cracks on temperature of the mould, it was checked, how the occurrence of cracks may influence distribution of temperatures in mould and whether it is possible to detect danger of breakout resulting from this fact by temperature probes. Calculations have proven that cracks are well identifiable by a thermocouple in the mould wall and it is possible to detect real danger of breakout with the use of the temperature probes.

REFERENCES

[1] D. Blažević, M. Ikonić, T. Mikac. Algorithm for preventiv of molten steel sticking onto mould in continous casting process. Metalurgija, 47 (2008), 47-50.

[2] C. Pinheiro, I. Samasekera, J. Brimacombe. Mould heat transfer and continuously cast billet quality with mould flux lubrication, Part 1 - Mould heat transfer. Ironmaking and Steelmaking, (2000) 1, 37-54.

[3] F. Chowaniec. Quality improvement of continuously cast round billets, Metalurgija, 47 (2008) 3, 191-193.

[4] Y. Meng, G. B. Thomas. Heat-transfer and solidification model of continuous slab casting. Metallurgical and Materials Transactions, (2003) 34, 685-705.

[5] M. Příhoda aj. Nové poznatky z výzkumu plynulého odlévání oceli. 1. vydání Ostrava : VŠB-TU Ostrava, (2001).

[6] M. Příhoda, J. Močkoř. Numerické řešení teplotního pole krystalizátoru při plynulém odlévání oceli. Hutnické listy, XXXXII (1987) 11, 790-795.