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HEAT-FLUX COMPUTATION FROM MEASURED-TEMPERATURE HISTORIES DURING HOT ROLLING

RAČUNANJE TOPLOTNEGA TOKA NA OSNOVI PRETEKLIH MERITEV TEMPERATURE MED VROČIM VALJANJEM

Jana Ondrouskova[1], Michal Pohanka[1], Bart Vervaet[2]

[1]Heat Transfer and Fluid Flow Laboratory, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, 616 69 Brno, Czech Republic
[2]Centre for Research in Metallurgy, Technologiepark 903c, 9052 Zwijnaarde, Belgium
ondrouskova@lptap.fme.vutbr.cz

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Due to the long service life of work rolls it is very important to follow the thermal load, but it is very difficult to measure it. One option for computing this thermal load is to measure the temperature and to study the thermal load through the heat flux. A unique work roll was made for testing different process conditions, such as rolling velocity, roll cooling, skin cooling and reduction. This work roll was tested on a real, hot-rolling, continuous pilot line. Two types of temperature sensors were embedded in the work roll in order to measure the temperature and these gave very detailed information about the development of the temperature inside the work roll. A time-dependent heat flux was computed using an inverse heat-conduction task with a detailed numerical model. The surface-temperature history was also obtained from this computational model. These boundary conditions give detailed information about the influence of different process conditions and allow a computation of the temperature field in the work roll. The paper describes the measuring equipment, details of the used temperature sensors, the inverse heat-conduction task for computing the thermal-surface boundary conditions and the results obtained from hot-rolling conditions.

Keywords: heat flux, hot rolling, roll cooling, inverse heat-conduction problem, surface temperature

Zaradi dolge dobe trajanja delovnih valjev je pomembno sledenje njihovih toplotnih obremenitev, ki jih je težko izmeriti. Ena od opcij izračuna termičnih obremenitev je merjenje temperature in študij toplotne obremenitve s toplotnim tokom. Izdelan je bil valj za preizkušanje različnih procesnih pogojev, kot so hitrost valja, ohlajanje valja, ohlajanje skorje valja in odvzem. Ta delovni valj je bil preizkušen na realni kontinuirni vroči valjarniški pilotni liniji. V delovni valj sta bili vgrajeni dve vrsti temperaturnih senzorjev, da bi izmerili temperature, in obe sta dali zelo podrobno informacijo o poteku temperature v njem. Izračunana je bila časovna odvisnost toplotnega toka z natančnim matematičnim modelom inverznega toka toplote. Iz tega računskega modela je bila dobljena tudi zgodovina temperature površine. Ti mejni pogoji so dali natančno informacijo o učinku različnih parametrov procesa in omogočili izračun temperaturnega polja v delovnem valju. V članku je predstavljena merilna oprema, detajli uporabljenih senzorjev temperature, inverzno prevajanje toplote za izračun mejnih termičnih razmer na površini in rezultati, dobljeni pri valjanju.

Ključne besede: toplotni tok, vroče valjanje, hlajenje valja, problem inverznega prevajanja toplote, temperatura površine

1 INTRODUCTION

The work roll is repeatedly heated and cooled during the hot-rolling process. A good knowledge of the temperature field of the work roll and a stress-strain analysis help us improve the cooling of the work roll and, thus, to extend its service life. The measurement of temperature histories inside the work roll during a hot-rolling trial was reported by Raudensky et al.[1] This article describes the results of the measurements in the pilot mill of CRM, Gent. The temperature sensors were embedded into the roll using inserts (as seen on the top of **Figure 1**). There were five thermocouples in each roll. An example of the data from the real measurement is on the bottom of **Figure 1**. The thermocouples were placed at two different depths. Two thermocouples were soldered at a depth of 0.4 mm (**Figure 1**) and three were drilled at a depth of 0.8 mm. A detailed description of the plug with a drilled shielded thermocouple and the discretization used for the computational model is given in[2].

2 INVERSE HEAT-CONDUCTION PROBLEM

A complex 2D-axis symmetric model was used for the numerical computation. The model includes the shielded thermocouple with all its parts and the used solder. The thermocouple must be taken into account because the homogeneity of the material is disturbed by the inserted thermocouple, and, thus, the temperature profile is also disturbed. One-dimensional sequential Beck's approach[3] is used for the computing of the heat fluxes and the surface temperatures. The main feature of this method is the sequential estimation of the time-varying heat fluxes and surface temperatures using the future time-step data to stabilize an ill-posed problem. The measured temperature history is used as input T^* to minimize the equation:

$$SSE = \sum_{i=m+1}^{m+f} (T_i^* - T_i)^2 \tag{1}$$

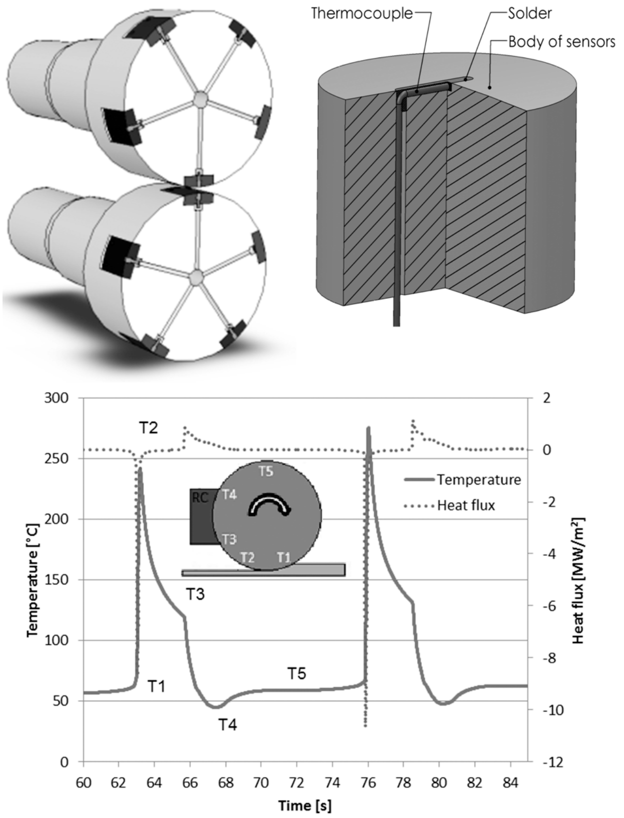

Figure 1: Cross-section of the rolls with the inserts from HiCr and HSS materials and the holes for the thermocouple wires; a detail of the plug with a soldered shielded thermocouple; temperature data of the two roll cycles (depth of 0.4 mm, speed of 0.1 m/s, reduction of 10 %)

Slika 1: Prečni prerez valja z vložki iz materialov HiCr in HSS in luknje za žico termoelementov; detajl čepa s prispajkanim termoelementom; podatki o temperaturah pri dveh ciklih valjanja (globina 0,4 mm, hitrost 0,1 m/s, odvzem 10-odstoten)

where m is the current time, f is the number of future time steps and T_i indicates the computed temperatures from the forward solver[4]. *SSE* denotes the sum of square errors. The value of surface heat flux q at time m is:

$$q^m = \frac{\sum\limits_{i=m+1}^{m+f} (T_i^* - T_i\big|_{q^m=0})\zeta_i}{\sum\limits_{i=m+1}^{m+f} (\zeta_i)^2} ; \zeta_i = \frac{\partial T_i}{\partial q_m} \qquad (2)$$

where ζ_i is a sensitivity coefficient of the temperature sensor at the time index i to the heat-flux pulse at time m. The temperatures $T_i\big|_{q^m=0}$ at the sensor location, computed from the forward solver, use all the previously computed heat fluxes without the current one, q^m. When the heat flux is found for time m, the corresponding surface temperature T_m^{surf} is computed from the forward solver. Using this procedure, the whole heat-flux history and surface-temperature history are computed.

3 RESULTS

The heat fluxes and surface temperatures computed using an inverse heat-conduction problem are presented here. The measured data were used for computing. **Figure 2** shows a comparison of the results obtained from the soldered and drilled sensor. It is obvious that faster changes can be studied with a thermocouple being implemented closer to the surface. During the measurements various parameters such as reductions (10 %, 30 % and 50 %, **Figure 3**), velocities (0.1 m/s, 0.3 m/s and 0.5 m/s), and roll cooling (on/off) were tested.

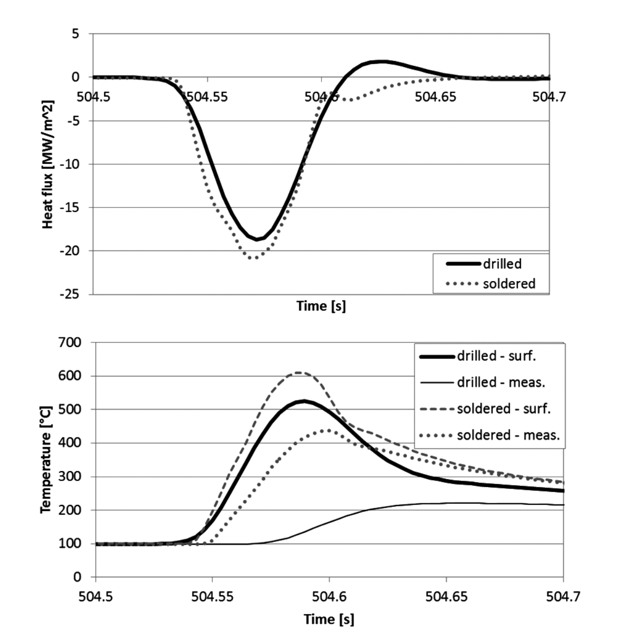

Figure 2: Comparison of the results obtained from the drilled and soldered thermocouple

Slika 2: Primerjava rezultatov, dobljenih iz izvrtanega oziroma prispajkanega termoelementa

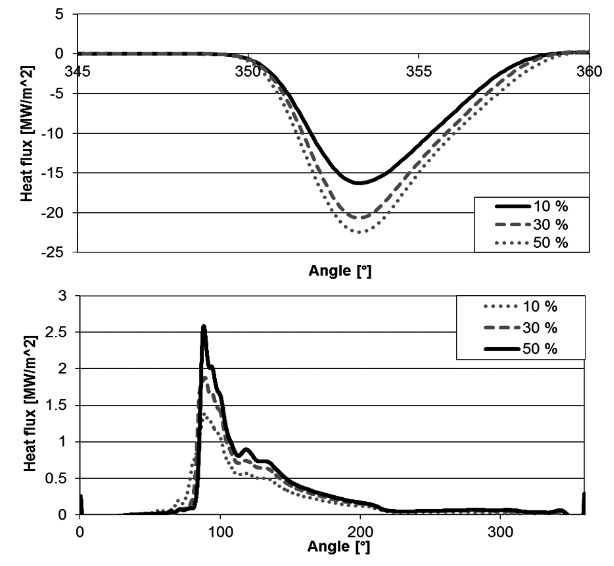

Figure 3: Influence of the slab reductions on the heat flux computed from the thermocouple situated 0.8 mm under the roll surface. The contact with the hot strip is on the top and the cooling of the roll is on the bottom.

Slika 3: Vpliv redukcije slaba na izračunan tok toplote, izračunan z uporabo termoelementa, nameščenega 0,8 mm pod površino valja. Zgoraj je prikazan na stiku z vročim trakom, spodaj pa ohlajanje valja.

4 CONCLUSION

An implementation of shielded thermocouples in a work roll used in a pilot mill of CRM, Ghent, was presented. Two types of plugs were used. One type had a soldered thermocouple very close to the surface and the other type had a thermocouple placed in a drilled hole that was 0.8 mm under the surface. An inverse algorithm, which enables a computation of the surface heat fluxes and surface temperatures from the measured temperature history inside a roll, was described. The presented results show the influence of the distance of the thermocouple from the investigated surface on the calculated surface-temperature and heat-flux accuracy. The closer the thermocouple is to the surface the faster changes can be investigated. The sensor with a soldered thermocouple gives a more accurate result as it is closer to the surface; however, the durability of this sensor is very low and it is destroyed after several contacts with the hot strip. On the other hand, the durability of a sensor with a drilled hole is much longer, but its results are not so accurate because the distance of the thermocouple from the surface is longer.

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