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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF THE TEMPERATURE FIELD OF A SOLIDIFYING MASSIVE DUCTILE-CAST-IRON ROLLER

NUMERIČNE IN EKSPERIMENTALNE RAZISKAVE TEMPERATURNEGA POLJA PRI STRJEVANJU LITEGA VALJA IZ SIVE LITINE S KROGLASTIM GRAFITOM

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The quality of the working rollers used for rolling rails of different profiles is determined by the chemical and structural composition of the material of the rollers and the production technology The requirements for the quality cannot be ensured without a perfect knowledge of the course of the solidification, the cooling and the heat treatment of the cast rollers as well as the kinetics of the temperature field of the casting and the mould. The solidification and cooling of the ductile-cast-iron roller in metal and non-metal moulds is a very complicated problem of heat and mass transfer with the phase and structural changes described by the Fourier equation. An original application of ANSYS simulated the forming of the temperature field of the entire system, comprising the casting, the mold and the ambient. The simulation of the release of the latent heats of the phase or structural changes is carried out by introducing the thermodynamic enthalpy function. In the experimental investigation of the temperature field, an original methodology for the measurement of the distribution of temperatures and heat flows in the roller-mould system had been developed and verified in operation. In the design of the original procedure, there were a number of problems connected with the large size of the roller and the mould, the uneven dimensional changes of the solidifying roller and the mould, the installation and the insulation of the thermocouples, the wiring of the thermocouple system, etc. The findings regarding the kinetics of the temperature field of the roller and the mould, obtained from experimental research, were used to determine the boundary conditions and for the verification of the numerical simulation program. The calculation of the temperature field focused on an analysis of the effect of the mould separator on the course of the solidification of the roller. The results of the mathematical modelling indicate that the distribution of the temperatures and the solidification in the vertical direction is significantly uneven – and this has an effect on the internal quality of the casting.

Keywords: spheroidized graphite cast iron (SGI), massive roller, solidification, temperature field, numerical model

Kakovost delovnih valjev za valjanje železniških tirnic različnih profilov je določena s kemijsko sestavo, mikrostrukturo in s proizvodno tehnologijo. Zahteve za kakovost ni mogoče zagotoviti brez popolnega poznanja poteka strjevanja, ohlajevanja in toplotne obdelave ulitih valjev ter kinetike temperaturnega polja ulitka in forme. Strjevanje in ohlajevanje ulitega valja, ki je ulit iz sive litine s kroglastim grafitom v kovinsko in nekovinsko formo, je zelo zapleten problem z vidika prenosa toplote in mase s faznimi in strukturnimi spremembami, ki jih opisuje Fourierjeva enačba. Z uporabo programskega paketa ANSYS-a je bilo simulirano temperaturno polje celotnega sistema, ki obsega ulivanje, formo in okolje. Simulacija prenosa latentne toplote faznih in strukturnih sprememb se izpelje z uporabo termodinamične funkcije entalpije. Pri eksperimentalni raziskavi temperaturnega polja je bila razvita izvirna metodologija za merjenje temperaturnega polja in toplotnega toka v sistemu valj – forma. V konstrukciji izvirnega postopka so številni problemi vezani z velikostjo valjev in forme, neenako dilatacijo pri strjevanju valja in forme, namestitvi in izolaciji termočlenov, napeljavi sistema termočlenov itd. Ugotovitve glede na kinetiko temperaturnega polja valja in forme, dobljene z eksperimentalnimi raziskavami, so bile uporabljene za določitev mejnih pogojev ter za potrditev numeričnega programa simulacije. Izračun temperaturnega polja je bil osredinjen na analizo učinka separatorja forme na potek strjevanja valja. Rezultati matematičnega modeliranja kažejo, da je porazdelitev temperatur in strjevanja v navpični smeri neenaka, kar vpliva na notranjo kakovost ulitka.

Ključne besede: siva litina s kroglastim grafitom, masivni valj, strjevanje, temperaturno polje, numerični model

1 INTRODUCTION

The solidification and cooling of these rollers – partly inside a sand mould and partly inside an iron mould – is a very complicated problem of heat and mass transfer with both phase and structural changes. An original application of ANSYS simulated the forming of the temperature field of the entire system. The introduced 3D model of the temperature field is based on the numerical finite-element method. Experimental research and temperature measurements must be conducted simultaneously with the numerical calculation in order to make the model more accurate and to verify it[1–3].

2 THE ASSIGNMENT AND PREPARATION OF THE INVESTIGATION

The assignment focused on investigating the transient 3D temperature field of a system comprising the casting, the mould and the ambient using a numerical model. The dimensions of the cylindrical casting and of the iron mould are given in **Figure 1**, while the diameter of the actual roller is 1180 mm with a height of 2100 mm.

This figure illustrates the entire set-up, comprising two parts of the sand mould for the upper and lower spindle ends and the iron mould. The working surface of the iron mould is covered with a separating layer – hereafter referred to as the "separator" (which is a special lubricant applied in various thicknesses to the inside walls of the iron mould and kiln-hardened at 180 °C prior to casting). The initial temperature of the mould was 20 °C, while the pouring temperature of the melt was 1336 °C. The casting was performed from underneath with a tangential in-flow. The total time of the casting of the spheroidal graphite cast iron (SGI) was 175 s.

2.1 Numerical model of the temperature field of the roller

The mathematical model for the simulation of the temperature field of the roller-mould system was created by ANSYS. The simulation of the release of the latent heats of the phase or structural changes is carried out by introducing the thermodynamic enthalpy function[4,5]. The program also considers the non-linearity of the task, i.e.:

- The dependence of the thermo-physical properties of all the materials entering the system
- The dependence of the heat-transfer coefficients (on all the boundaries of the system) on the temperature of the surface of the casting and mould.

A series of experimental temperature measurements was conducted for the verification of the model and the closer determination of the boundary conditions of the numerical solution of the temperature field. The results from the experimental measurements were used for the verification of the model and the correction of the boundary conditions for the numerical solution of the temperature field. The calculation of the temperature field dealt mainly with the effect of the separator between the casting and the iron mould on the solidification of the roller.

2.2. The results of the simulation of the temperature field with respect to the separator thickness[1]

The thicknesses of the separator – for individual simulations of the solidification and cooling of the roller – were (0, 5, 10 and 15) mm. The point where the melt solidifies last is the centre – 2100 mm from the base of the iron mould. The centre of the body of the roller is on the axis at a distance of 1050 mm from the same base. **Table 1** contains the solidification times of the roller, which are calculated from the simulation.

Table 1: Solidification times for various separator thicknesses
Tabela 1: Čas strjevanja pri različnih debelinah separatorja

Separator thickness	Solidification time			
	Centre of roller		Entire roller	
(mm)	*t*/h	*t*/s	*t*/h	*t*/s
15	8 187	29 473	8 783	31 618
10	7 845	28 242	8 124	29 246
5	7 030	25 310	7 531	27 111
0	6 510	23 437	6 554	23 593

Figures 2 and **3** illustrate the temperature field along the longitudinal axis of the system without the separator and with a 15 mm separator after 7.845 h, i.e., at the time when the centre of the roller solidifies with a separator that has a mean thickness of 10 mm (**Table 1**).

It is possible to observe an enlargement of the above-mentioned red area along the vertical axis with an increasing thickness of the separator. **Figure 4** shows the dependence of the total solidification time of the centre of the roller and the entire roller on the separator

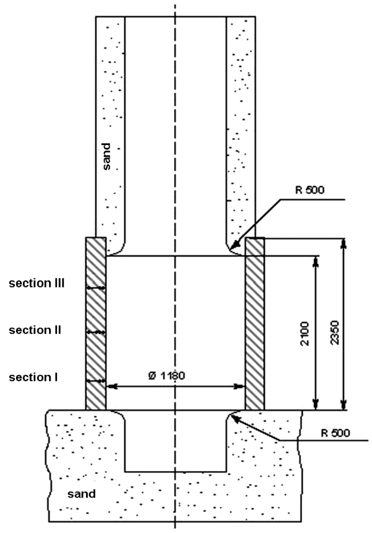

Figure 1: The set-up of a vertically cast
Slika 1: Sistem vertikalnega ulivanja

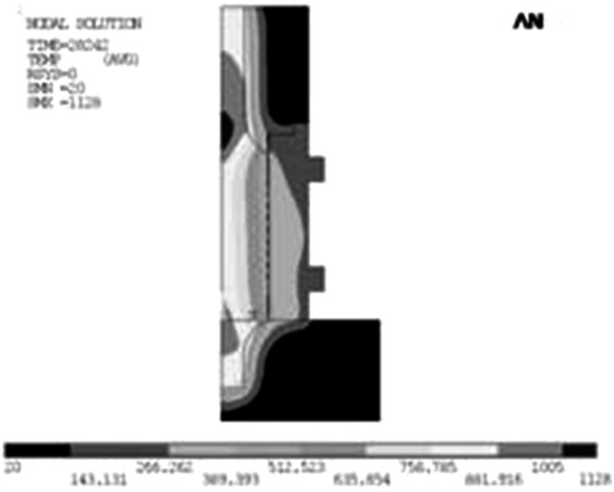

Figure 2: The temperature field along the longitudinal section (without the separator)
Slika 2: Temperaturno polje po vzdolžnem prerezu (brez separatorja)

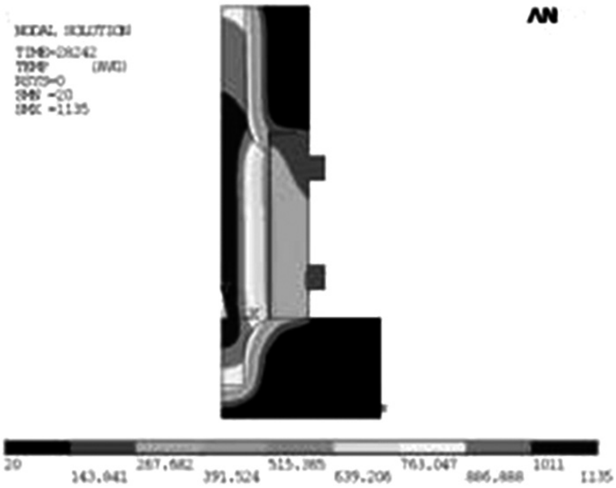

Figure 3: The temperature field along the longitudinal section (with a 15 mm separator)

Slika 3: Temperaturno polje po vzdolžnem prerezu (s separatorjem 15 mm)

thickness. The relationship between the separator thickness and the solidification time can be described in great detail using the linear function – as the reliability coefficient values in **Figure 4** indicate for both straight lines. The separator has proven to be a good insulator. The solidification time of the roller inside the mould with a 15 mm separator increases by up to 26 % compared to that without the separator.

3 EXPERIMENTAL MEASUREMENT OF THE TEMPERATURES INSIDE THE PERMANENT MOULD AND ON THE SURFACE OF THE ROLLER

The distribution of the temperatures along the height of the iron mould and roller (**Figure 5**) was measured in three horizontal planes, 100 mm (section I), 1000 mm (sect. II) and 1950 mm (section III), from the bottom edge of the iron mould (**Figure 1**).

The inner surface of the permanent mould, i.e., point 9), was selected for the comparison of the temperatures from the numerical simulation with the experimentally obtained temperatures from inside the iron mould.

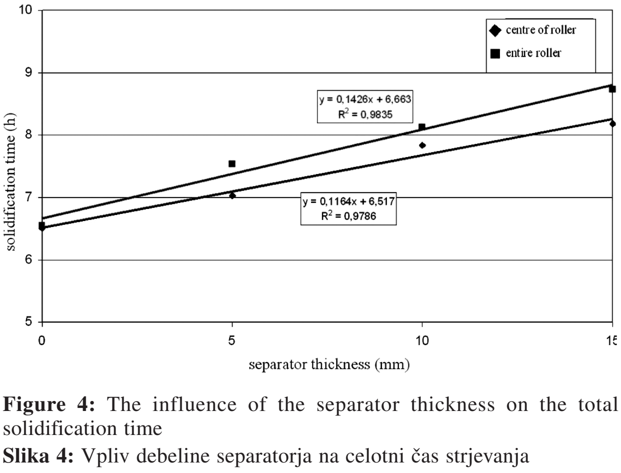

Figure 4: The influence of the separator thickness on the total solidification time

Slika 4: Vpliv debeline separatorja na celotni čas strjevanja

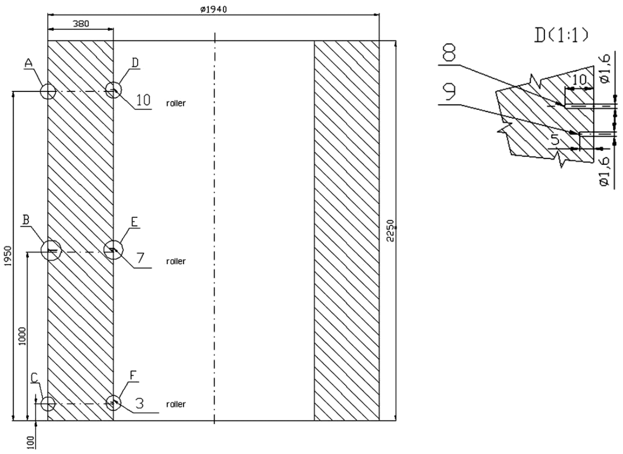

Figure 5: Layout of measurement points

Slika 5: Položaj merilnih točk

Figure 6 confirms the very close similarity between the calculated and measured temperatures of the permanent mould. It appears that the absolute values and the histories of the experimental and calculated temperatures in the points of the cylindrical casting and iron mould, which had been selected for comparison, are very similar. The determined relationship between the solidification time (of the entire casting or its geometrical centre) and the thickness of the separator applies. The simulation of the temperature field of the roller and the mould (using ANSYS) can therefore be considered to be successful.

The results of the mathematical model indicate that the distribution of the temperatures and the course of the solidification in the vertical direction is relatively uneven, which affects the internal quality of the casting. While the body of the roller is solidified along the entire height, the temperatures are still high in the lower spindle and could be the cause of the shrinkage porosity at the point where the spindle enters the roller. That is why the lower spindle should solidify in a mould with a higher heat accumulation, i.e., in a mould made of CT-CrMg or in an iron mould. A sooner topping-up of

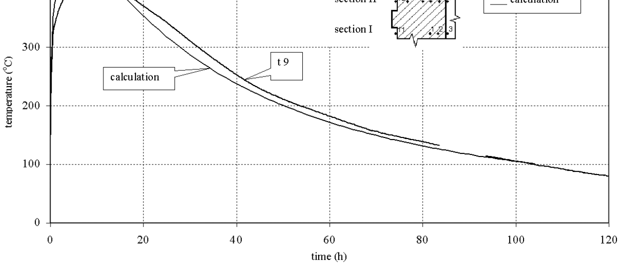

Figure 6: Calculated versus measured temperatures (point 9)

Slika 6: Izračunane temperature v primerjavi z izmerjenimi (točka 9) the upper spindle should ensure replenishing of the mould with melt into the body of the roller in order to achieve increased quality.

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