ISSN 1392 - 1207. MECHANIKA. 2013 Volume 19(4): 398-402

Failure analysis of continuous casting rolls material and physical simulation of thermal fatigue loading

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crossref http://dx.doi.org/10.5755/j01.mech.19.4.5046

1. Introduction

The incidents of in-service failure in continuous casting machines (CCM) rolls are connected with the nucleation and propagation of crack-like defects on their working surface [1]. Since the rolls are operated under conditions of thermomechanical loading, the structural and mechanical degradation of the material surface layers takes place, as well as lowering of their strength and exhaustion of plasticity [2, 3]. In the process of operation, dynamic overloading of the structure may occur, therefore it is necessary to reveal the regularities in dynamic failure of the CCM roll material with in-service defects at operating temperatures [4]. Another important task is to create physical models of CCM rolls, which would allow reproducing temperature conditions of the continuous casting process, and providing for the possibility to calculate the stress-strain state of the structure [5, 6]. The purpose of this work is to investigate temperature conditions of the CCM roll operation on a specifically developed physical model, and assess impact toughness of the CCM roll material with in-service defects.

2. Research technique of thermocyclic loading

In order to simulate the in-service thermocyclic loading of the CCM roll surface layers (Fig. 1) the roll model was performed in the form of a hollow thick-walled cylinder from steel 25Kh1M1F with the length of 200 mm and the diameter of 60 mm. The cooling outlet with the diameter of 12 mm was performed along the roll axis.

The roll model was fixed on a shaft with the longitudinal outlet installed on a sliding bearing support, through which running water was pumped.

The roll of the synchronous motor with the TsD-54 reducer was rotated at a low speed through a step-down V-belt transmission [7, 8]. The frequency of the roll rotation was 0.01 Hz, which corresponds roughly to operating conditions [1, 2].

The operating temperature of the roll surface was provided by heating the roll with the gas burner. Readings of the chromel-alumel thermocouples installed at a distance of (h = 0; 5.0, 15.0 mm) from the roll surface were recorded. The temperature was controlled visually by the digital voltmeter readings. The roll was cooled by dipping its lower part into the container with cold running water, Fig. 1.

Thermocouples for measurement of temperature fields were fixed in the roll body. The signal from thermocouples was transferred through modules I -7016 to module I-7017F, which is an 8-channel ADC module (up to 10 meas./s). Interface module I-7520 was used to connect the data recording system to the PC. A separate unit provided power to the system modules (U = 24 V, I = 1.5 A).

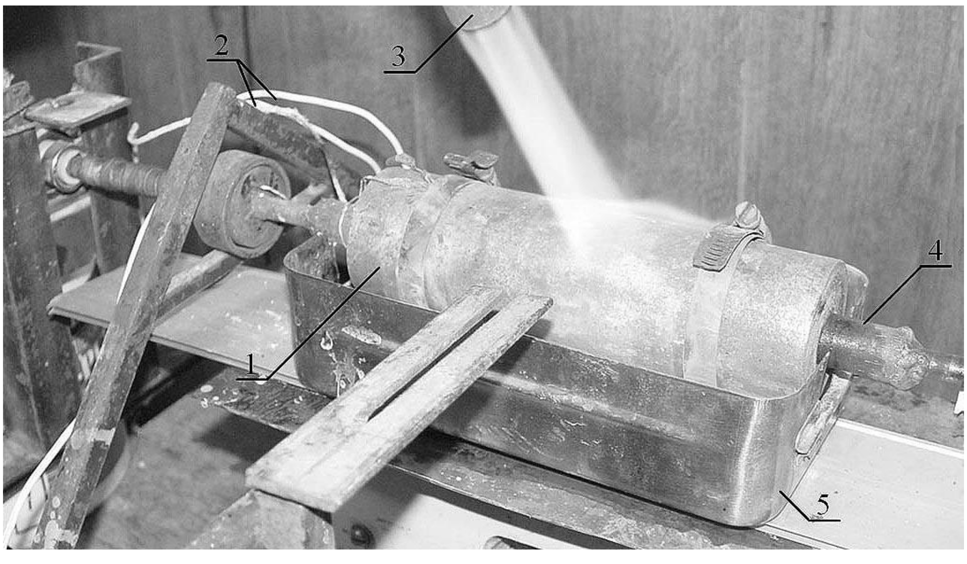


Fig. 1 Scheme of physical model of the CCM roll for investigation of thermal fatigue: *1* – roll; *2* – chromel-alumel thermocouples; *3* – gas burner; *4* – hollow shaft, *5* – container for cooling

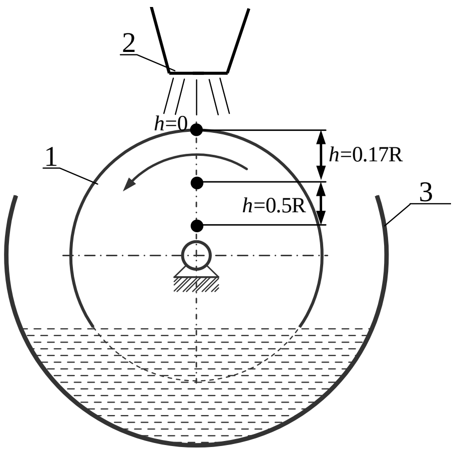
Since the length of the roll model is 3.3 times greater than its diameter, temperature fields were measured in its central part. Moreover, the variation of temperature along the roll axis was not taken into account while solving a two-dimensional problem in a separately taken cross-section [5]. Halting of the process of pouring for 1.0 minute was modeled, Fig. 2. It was found that after a start of the roll heated to the quasi-stationary condition an insignificant lowering of the cycle temperature took place followed by its stabilisation during the next 4-5 rotations. On the whole, the experimental data (T_{max} = 600°C, T_{min} = 90°C) were close to the in-service ones (T_{max} = 580°C, T_{min} = 130°C). The graphs showing the dependence of the axisymmetric component of the roll temperature field on the rotation time were plotted, Fig. 3.

The maximum value of temperature (600°C) on the external roll surface was attained at the maximum point of the cycle during a contact with the source of heating, the minimum value – during cooling in the container (90°C).

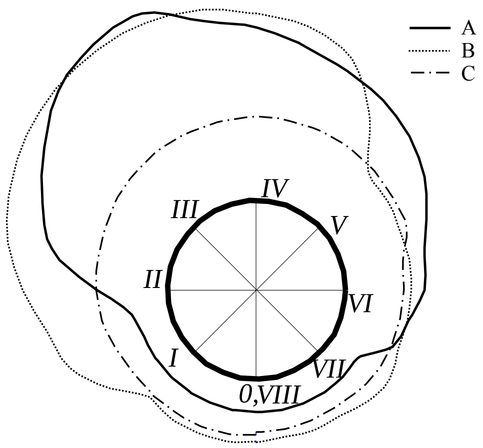
Due to intensive heat outflow from the internal layers the temperature at the lower point of the cycle was stable for 35 seconds. The analysis of the investigation results (Fig. 2, a, b) showed that with an increase in the angle of contact between the roll and the source of heating the duration of the roll transition to the stable mode decreases. This is connected with a faster and more uniform heating of the roll model. It should be noted that halting of the roll causes an increase in temperature of near-surface layers; moreover, the thermal cycle amplitude approaches the values obtained on the surface, Fig. 2, b. The roll rotation causes the occurrence of the periodic and non-periodic components of the temperature field, Fig. 3, b. The non-periodic component of the temperature field occurs in transitional modes only. The periodic component is typical of the technological process and is localised in the surface layer [1]. In the quasi-stationary mode investigated, the active zone with a periodical variation of temperature exists, as well as the axisymmetric kernel, which is practically invariable during one rotation [5]. Experimental temperature measurement along the radius for CCM roll model is shown in Table.

Visualisation of the thermal cycle (Fig. 3, a) allowed assessing a change in its shape. A “sharp” thermal cycle of the triangular shape is characteristic of the surface layer.

With an increase in the distance from the surface it acquires a “smoothened” shape. The maximum amplitude of the thermal cycle was observed on the model surface. With a decrease in the $\overline{R} = R_i / R_{\max}$, (where R_i - measurement radius and R_{max} - maximal radius of roll) value the thermal cycle amplitude decreases (Fig. 3, b). A decrease in the thermal cycle amplitude within internal layers of the CCM roll was caused by a lower intensity of the heat outflow and a transition to the quasi-stationary temperature field. The results obtained agree satisfactorily with the in-service data obtained on the industrial continuous slab and billet casting machines [9-11].



a



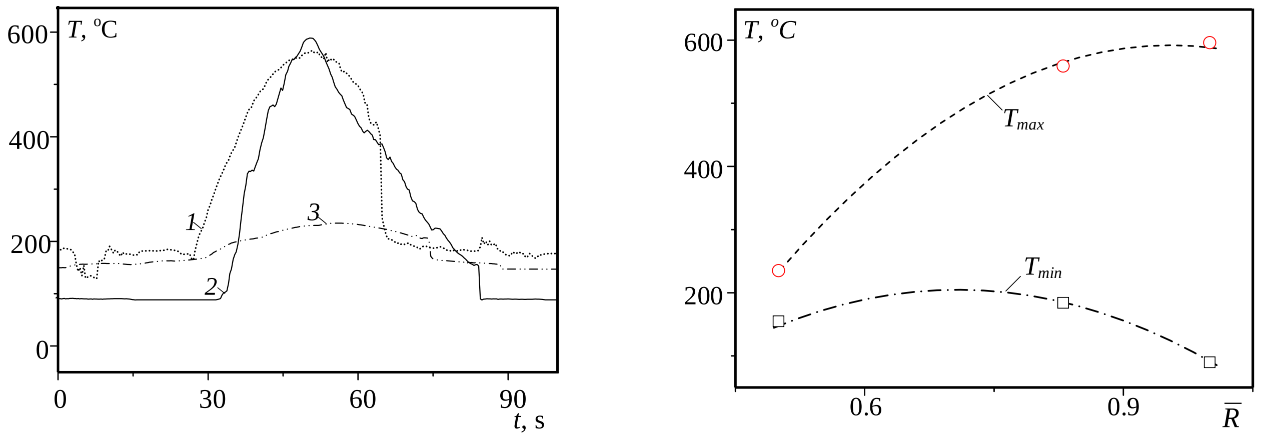
b

Fig. 2 Scheme of thermocyclic loading a) roll - *1*, gas burner - *2*, container for cooling - *3* and temperature fields in the roll body b) at distances h = 0 mm; 5.0 mm; 15.0 mm (*A* ,*B*, *C*), respectively, from the working surface after 5.0 minutes’ halt; (0 - VIII – temperature measurement point)

Table

Temperature field parameters in the CCM roll model

Measurement point	Distribution of temperature (T) along the radius of roll, °C		
	R	0.17R	0.5R
0	92	174	156
I	92	176	164
II	198	407	200
III	538	547	224
IV	485	523	234
V	357	200	219
VI	221	186	163
VII	94	190	151



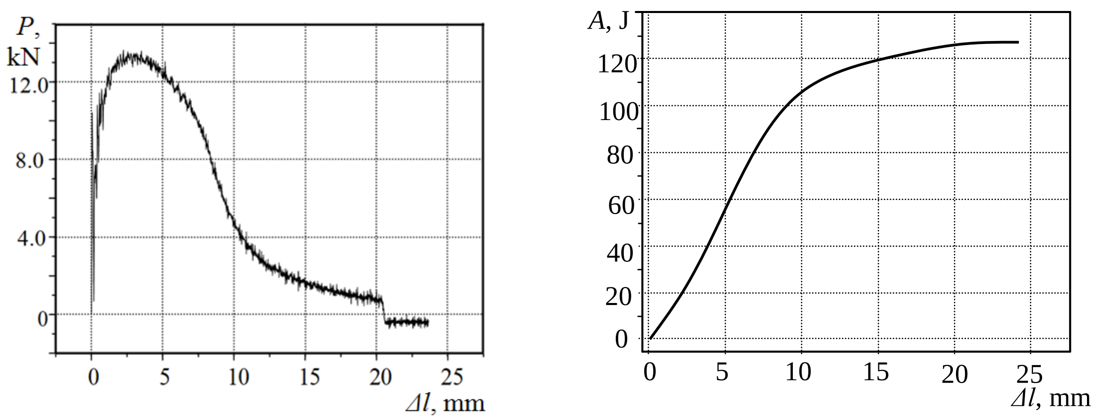
a b

Fig. 3 Thermal cycles in the body of the roll model at distances h = 0 mm (1); 5.0 mm (2); 15.0 mm (3) from the surface (a), maximum and minimum temperatures of thermal cycle (b)

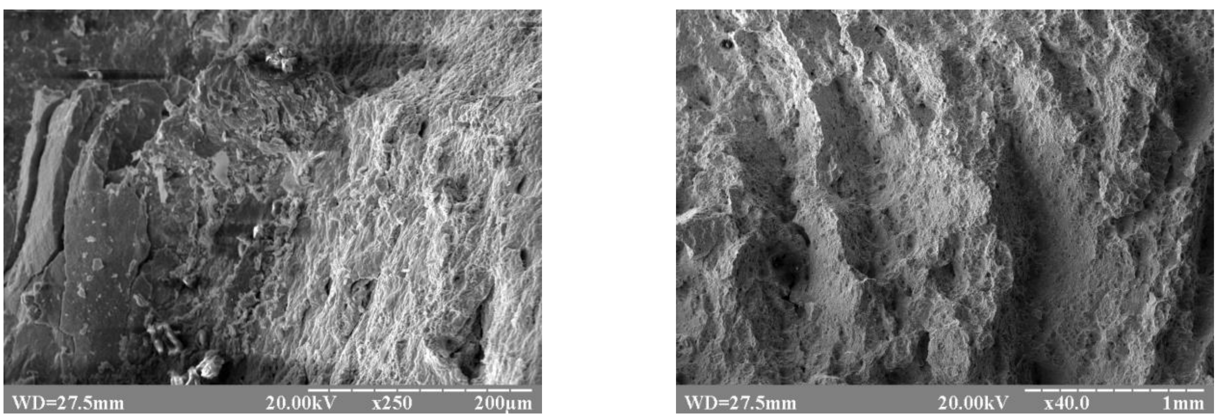
3. Effect of operating temperatures on impact toughness of the roll material

Steel 25Kh1M1F, which is used for the production of CCM rolls, has a typical ferritic-pearlitic structure, which contains ferritic grains of 20…30 μm and pearlitic grains of 30…40 μm. The preliminary electronic and microscopic investigations showed that the ferritic grains are characterised by the presence of a small number of chaotically spread dislocations. In the body of ferritic grains and on their boundaries, carbide particles of the round and ellipse-like shape with sizes of 2…7 μm were found. The average thickness of cementite plates was 0.05 μm, and the distance between them was 0.13 μm [12].

Impact toughness was determined on the Charpy specimens with dimensions 10×10×55 mm, which had V-like notches and the radius of 0.25 ± 0.025 mm. The specimens were cut from the surface layer of the CCM roll. The tests were performed on the RKP-300 impact testing machine with the impact energy of 300 J; loading diagrams in coordinates “impact force – time” and “impact force – specimen bend” were recorded, Fig. 4, a, b.



a b



c d

Fig. 4 Diagrams of deformation (a), change of fracture energy (b), crack start (c) and propagation (d) zone in the Charpy specimen at 600°C

The cutting scheme and the shape of the Charpy specimens for impact toughness tests were chosen to suit the task of modeling crack propagation in the CCM roll during operation. In the process of the CCM roll operation, fatigue cracks nucleate on the roll surface and propagate in the radial direction.

Impact toughness was determined from formula:

$$KCV = \frac{A}{F},$$

where A is the specimen fracture energy, J; F is the cross-sectional area of the specimen in the place of a notch, mm^2.

The "VUHI-CHARPY" programme for controlling and recording the impact test data allows determining the specimen fracture energy components by means of transforming the loading-time (P-t) dependency into the loading – deflection (P-s) one.

The impact toughness (KCV) of the material after service at the temperature 600° is 1.5 MJ/m^2. Material characteristics were analysed by the shape of the loading diagram under conditions of impact loading during the crack nucleation and propagation, Fig. 4, c, d. The diagram has practically no section of the unstable crack start, the graph has a cupola-like shape. Plastic deformation of steel 25Kh1M1F at the crack tip causes an increase in the energy expenditure on the material failure during the crack nucleation and propagation. Charpy specimens investigated are characterised by significant sections of local and general deformation, which cause the formation of separation dimples on the fracture surface. Large dimples have predominantly the round shape, they are decorated with smaller dimples and are separated by plastically deformed ridges is shown in Fig. 4, d. This testifies to the homogenisation of the specimen structure, lowering of its structural and mechanical non-uniformity, and activation of the thermal annealing processes [13, 14].

High temperatures activate relaxation processes providing for a more homogeneous distribution of tensile stresses along the specimen cross-section. This leads to the formation of the homogeneous fracture front with the sections of local shear in places where the direction of the main crack propagation changes. Fracture surface is formed by the longitudinal shear scheme, which transforms into the "shear + turn" scheme leading to the formation of high separation ridges [15].

4. Conclusions

The procedure is developed and the experimental setup is created for physical modeling of operating conditions of the CCM roll with the automated recording of measurement results. The temperature field with the service casting speed was simulated.

The temperature fields at different roll radius were investigated. The main regularities in temperature distribution in the CCM roll cross-section are found during its stable rotation at the industrial frequency.

The macro- and micromechanisms of failure in Charpy specimens are investigated, which are cut from the CCM roll surface with crack-like defects.

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TOLYDINIO LIEJIMO MAŠINOS RITINĖLIO MEDŽIAGOS IRIMO ANALIZĖ IR JO TERMINIO NUOVARGIO FIZINIS MODELIAVIMAS

R e z i u m ė

Sukurtas laboratorinis metodas tolydinio ruošinių liejimo mašinos ritinėlio eksploatacinėms sąlygoms modeliuoti. Jo fizinis modelis leidžia automatiškai užrašyti kvazistacionaraus temperatūrinio lauko pokyčius ritinėlio paviršiniame sluoksnyje ir įvairiais atstumais nuo jo darbinio paviršiaus. Ištyrinėtas ritinėlio irimo nuo smūginės apkrovos mechanizmas, esant maksimaliai terminio ciklo temperatūrai.

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FAILURE ANALYSIS OF CONTINUOUS CASTING ROLLS MATERIAL AND PHYSICAL SIMULATION OF THERMAL FATIGUE LOADING

S u m m a r y

The experimental method for physical modeling of operating conditions of a continuous billet casting machine (CCM) rolls is developed to estimation the temperature field and especially the temperature at the surface of the roll by measuring the temperature with the thermocouples (fully embedded) at multiple point inside the roll.

The physical model allows for the automated recording of the quasi-stationary temperature field in the rolls surface layers and at various distances from its working surface. The main mechanisms of impact failure in the service exposed CCM roll material are investigated at the maximum temperature of the thermal cycle.

Keywords: thermal fatigue, high temperature, failure, roll.

Received February 28, 2012
Accepted June 17, 2013