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Modelling surface degradation in hot rolling work rolls

Modeliranje degradacije površine valjev za vroče valjanje

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Abstract

For better understanding of materials behaviour subjected to thermal fatigue of work rolls used in hot rolling mill, two thermal fatigue tests were developed. Tests were performed using Gleeble 1500D thermo-mechanical simulator. The first test was applied for the testing of thermal fatigue resistance of work rolls used in common rolling conditions. The average cracks length and the crack density of the specimens were established at varying test temperatures and the number of thermal fatigue cycles. The second test enabled the simulation of the thermal loading of the work rolls during a rolling mill stall. The growth of stall band firecracks after different cooling condition of the work rolls is presented.

Key words: hot rolling, work roll, thermal fatigue, fire cracks

Izvleček

Za boljše razumevanje vedenja materiala izpostavljenega termičnemu utrujanju delovnih valjev, ki se uporabljajo za vroče valjanje, sta bila razvita dva preizkusa za termično utrujanje valjev. Preizkusi so bili izvedeni z uporabo termomehanskega simulatorja Gleeble 1500D. Prvi preizkus je bil uporabljen za preizkušanje odpornosti proti termičnemu utrujanju delovnih valjev v normalnih razmerah valjanja. Za določitev povprečne dolžine in gostote razpok so bili preizkusi izvedeni pri različnih temperaturah in številu ciklov termičnega utrujanja. Drugi preizkus omogoča simulacijo toplotne obremenitve delovnih valjev med zastojem valjalnega stroja. Prikazana je rast razpok v vročem glede na različne razmere pri ohlajanju delovnih valjev.

Ključne besede: vroče valjanje, delovni valj, termično utrujanje, razpoke v vročem

Introduction

Work rolls represent an important segment in the operating cost of a modern rolling mill. They are expensive and a large number of work rolls must be in stock to assure the continuous operating of the mill. During hot rolling work, rolls are subjected to successive heating and cooling conditions. Their surface is exposed to rapid temperature changes due to the contact with hot rolled material and due to cold water used for work rolls cooling. This cyclic heating/cooling conditions cause thermal fatigue which is one of the most important factors affecting the rate of surface deterioration as well as mechanical fatigue and abrasion. Thermal fatigue is a low-cycle failure mechanism that occurs due to the cyclic thermal loading of the work rolls surfaces.

Cooling process of the work rolls is one of the most important tasks during hot rolling. Their surface is exposed to rapid temperature change due to the contact with hot rolled material and cooling with water sprays. If cooling is not intensive enough, wear of rolls and fire cracks appear. Fire cracks can appear after only a few turns of rolls, starting on the surface and growing perpendicular to the surface of the rolls. The intensity of the growth and the depth of the cracks mostly depends on the temperature gradient during alternating heating and cooling[1–3].

The evolution of work roll surface temperature during one revolution is presented in Figure 1[4]. The work roll is divided into angular sections. In the section 1, a high increase of the roll surface temperature is noticed. The reason is in the heat transfer from the hot slab to the roll. The contact time between the slab and the roll is very short, only the skin of the roll is subject to the very high thermal gradients. In section 2, the work roll slowly cools down due to radiation and convection. In section 3, the surface temperature decreases during water cooling. In sections 4 and 5, the surface temperature rises slightly due to the heat transfer from the roll centre. A drop of the surface temperature due to the contact with the back-up roll occurs. In section 6, the temperature decreases due to the water cooling and in section 7, the surface temperature rises due to the radiation of the slab surface.

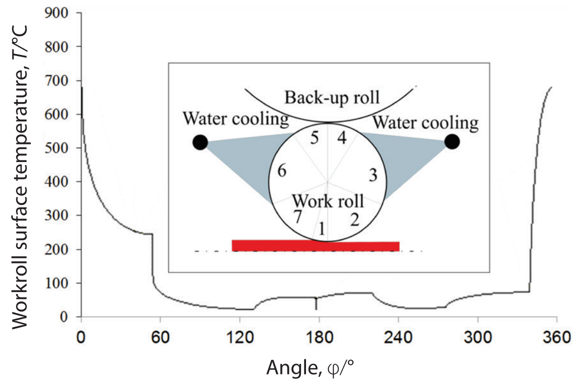

Figure 1: *Evolution of work roll surface temperature.*

In this paper, two different tests for the laboratory assessments of the thermal fatigue resistance of work rolls are presented. The first test enables a simulation of the thermal fatigue of work rolls during hot rolling of flat products at common condition[5–7]. Furthermore, with the second test, the thermal fatigue resistance of work rolls in the case of the rolling mill stalls can be investigated. Both tests were implemented in a thermo-mechanical simulator of metallurgical states, the Gleeble 1500D. The resistance heating and the water cooling of the samples as well as air blowing (water emptying process) were computer-controlled. The samples were freely spanned in the working jaws of the Gleeble loading system, keeping the outer force on the samples at 0 N.

Experimental

Specimen

Specimens were machined from the work rolls. They were cylindrically shaped with a borehole in the longitudinal axis that enabled the cooling of the specimens with a stream of water and air (Figure 2). The reduction of the diameter in the central part of the specimen intensified the temperature gradient during the heating and the cooling stage of the experiment. The temperature was controlled with the thermocouple that was spot-welded in the middle of the reduced part of the specimen (Figures 2, 3).

The thermal fatigue tests were performed on thermal-mechanical simulator Gleeble 1500D.

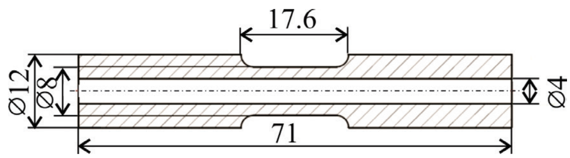

Figure 2: *Specimen.*

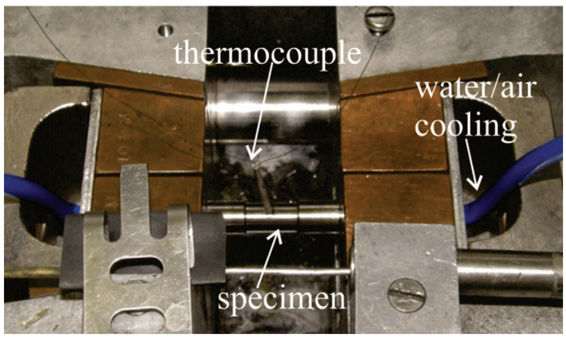

Figure 3: *Test cell with specimen, Gleeble 1500D.*

Thermal fatigue of work rolls

Specimens were tested at similar conditions found on the surface of rolls during hot rolling. Specimens were heated to four different temperatures, 400 °C, 500 °C, 600 °C and 700 °C and then rapidly cooled with water and air. Two series of experiments with 500 and 1 000 thermal fatigue cycles were carried out. Each cycle was composed of three phases: resistance heating, water cooling and cooling of the specimen with air, all in duration of 4.8 s.

Material

The specimens were electric-discharge machined from an indefinite chill roll. All these rolls were cast as a double layer. The hard working surface consisted of matrix of dendrite grains from bainite and martenzite, ledeburite and some free graphite. The core of the roll can be made either out of the alloyed grey cast iron or out of the alloyed nodular cast iron. These types of roles are used for roughing and finish rolling mills. The typical chemical composition is listed in Table 1.

Table 1: *Typical chemical composition of the indefinite chill roll in mass fractions, w/%*

	C	Si	Mn	Cr	Ni	Mo
min.	3.0	0.8	0.2	1.4	4.0	0.2
max.	3.4	1.1	0.5	2.0	4.6	0.5

Stall band firecracks

For the investigation of the formation of stall band firecracks on the work roll surface, five tests were performed.

For the first test, the specimen was heated up to 600 °C for each thermal fatigue cycle and then cooled down with a stream of water and air. This was a base test condition for all other tests. After 500 cycles, the specimens were held at the testing temperature for 15 s or 60 s and then cooled down to the room temperature with water or air (Figure 4).

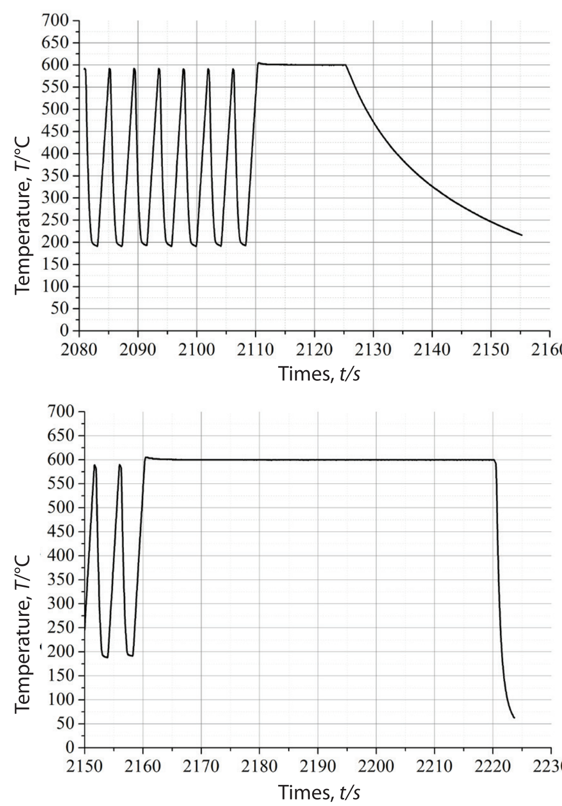

Figure 4: *Measured temperature a) holding time t* = 15 s, *free air cooling; b) holding time t* = 60 s, *forced water cooling.*

Material

The specimens were machined from high chromium iron rolls. These are double layer centrifugal cast compound rolls: with the cast iron outer layer with high chromium content and the core made either of a grey or a nodular cast iron. Work surface contains very hard chromium carbides, fine grained and equally distributed within the matrix which is made mainly from pearlite as well as the tempered martensite. High chromium rolls are used for hot rolling of flat products. The typical chemical composition is listed in Table 2.

Table 2: *Typical chemical composition of the high chromium iron roll in mass fractions, w/%*

	C	Si	Mn	Cr	Ni	Mo	V
min.	1.0	0.5	0.6	10.0	1.0	1.0	0.2
max.	2.0	1.0	1.2	13.0	2.0	2.0	0.5

Results and discussion

Temperature measurement

Temperature was measured at the centre of the exterior surface of the specimen. The wall thickness of the specimen was 2.0 mm. This is one of the reasons why the measured cooling temperature is not in accordance with the programmed one (Figure 4). The Figure 4 represents the course of the programmed temperature (black curve), the measured temperature (red curve) and the rate of the change of the temperature during testing.

The cooling rate increased with the increasing test temperature. At the test temperature 400 °C, the cooling rate was 300 °C/s and at the test temperature 700 °C, the cooling rate was 550 °C/s.

The entire time for one thermal fatigue cycle was composed of 2.2 s of resistance heating to the test temperature, 1.8 s of water quenching, and 0.8 s of forced air cooling. During the water cooling, the cooling rate was at 136 °C/s, and during the air cooling it decreased to 13 °C/s.

Thermal fatigue of work rolls

During the testing thermal fatigue, cracks appeared on all of the specimens. Cracks start to grow on the cooled surface of the specimen on the phase boundaries between grains of bainite and martensite and grains of ledeburite. Cracks propagate in depth of specimen mostly through the ledeburitic phase, (Figure 6).

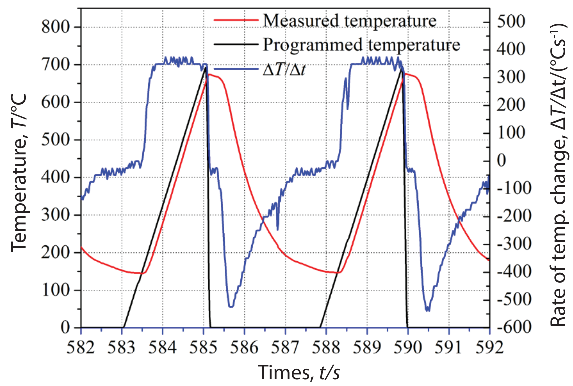

Figure 5: *Testing conditions: A – resisting heating, B - water quenching, C – air cooling.*

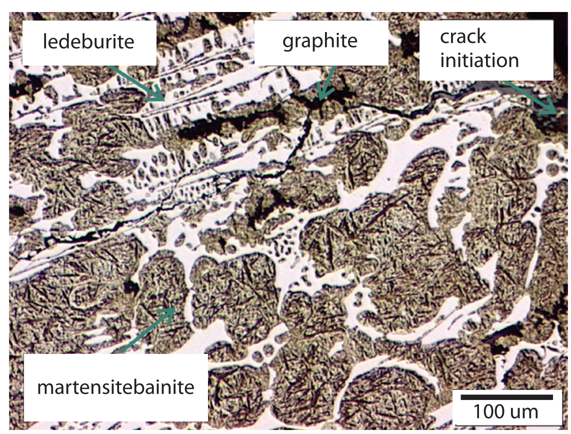

Figure 6: *Crack propagation, T = 700 °C, 500 cycles.*

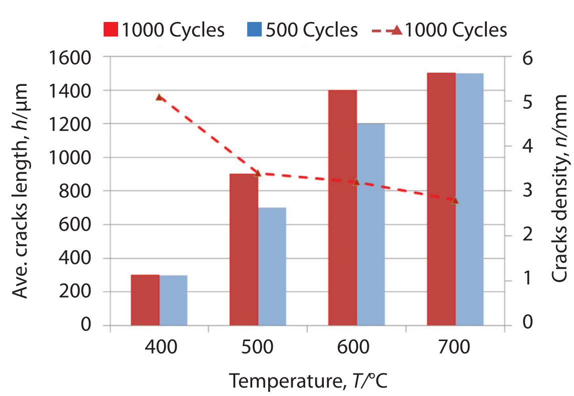

Figure 7: *Average cracks length and crack density.*

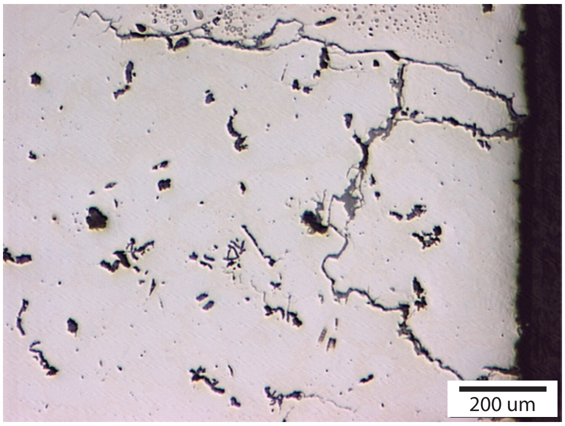

Figure 8: *Linking of cracks.*

With a higher test temperature during a single cycle and a higher number of cycles, cracks become wider and deeper, but lower in density. At the temperature of 400 °C, 5.1 cracks/mm were formed on average. At the temperature of 700 °C, the density of cracks was reduced to 2.8 cracks/mm. In the 2.0 mm thick wall of specimens, cracks reached a length between 300 µm and 1 500 µm (Figure 7).

At higher temperature, the cracks can link together and subsequent spalling of roll surface fragments may occur (Figure 8).

Stall band firecracks

During a mill stall or a sudden stop of the rolling mill, the hot rolled strip is in contact with the work roll surface for an extended period of time. Due to extended (lasting up to several minutes) holding of rolls at high temperatures (850 °C–1 250 °C), the local overheating of work rolls appears. During that, the overheated surface expands in radial direction and contracts in axial and tangential direction. When the remaining stresses exceed the yield strength of the material, the stall band firecracks form with net-like shape (Figure 9).

Figure 9: *Stall band firecracks at the work roll surface.*

The main task after this type of incident is to minimize the severity of the cracking that will result. There are several procedures at our disposal:

- to remove the rolls from the rolling mill,
- to rotate the rolls for about half an hour without water cooling or
- to cool down rolls with the water cooling system.

In the present work, the simulation of stall band firecracks growth of the work rolls after different cooling condition is presented. The mill stall was simulated with 500 thermal fatigue cycles followed by 15 s or 60 s holding time at the test temperature of 600 °C and then finished with forced water cooling or free air cooling.

In general, the lengths of firecracks were in the range of 5 mm to 422 mm. The largest average crack length and the lowest crack density were obtained in specimens, which were free cooled on air (Figures 10, 11, 12). The crack density and the average cracks length obtained at the holding time of 15 s are similar to the base test (Figures 11, 12).

From these results we can draw the conclusion that the best procedure to reduce firecracking of the work rolls after the rolled material is removed from the roll gap is forced cooling of the work rolls with water. In this case the density of firecracks is higher, but the lengths of the cracks are shorter. The growth of the cracks is accelerated by the cracks oxidation while the oxides have bigger volume than the base material and they act as the wedge to the crack. The oxide thickening is accelerated by the increase in temperature[1].

The SEM miocrograph of the oxidated firecrack is shown in Figure 13a and the related EDS spectra in Figure 13b. These results are contradict the findings found in the literature[6]. It is suggested that after the rolled material is removed from the roll, the water cooling should be turn off. Extended contact times with rapid water cooling will result in a larger cell size and deeper cracks. Once the rolled material has been removed from the roll gap, the rolls should be rotated for a minimum of 20 min to allow equalization of the roll surface temperature. Further testing will be carried out to optimize the cooling time of the rolls, which would contribute to decrease in down-time of the rolling mill after such an event.

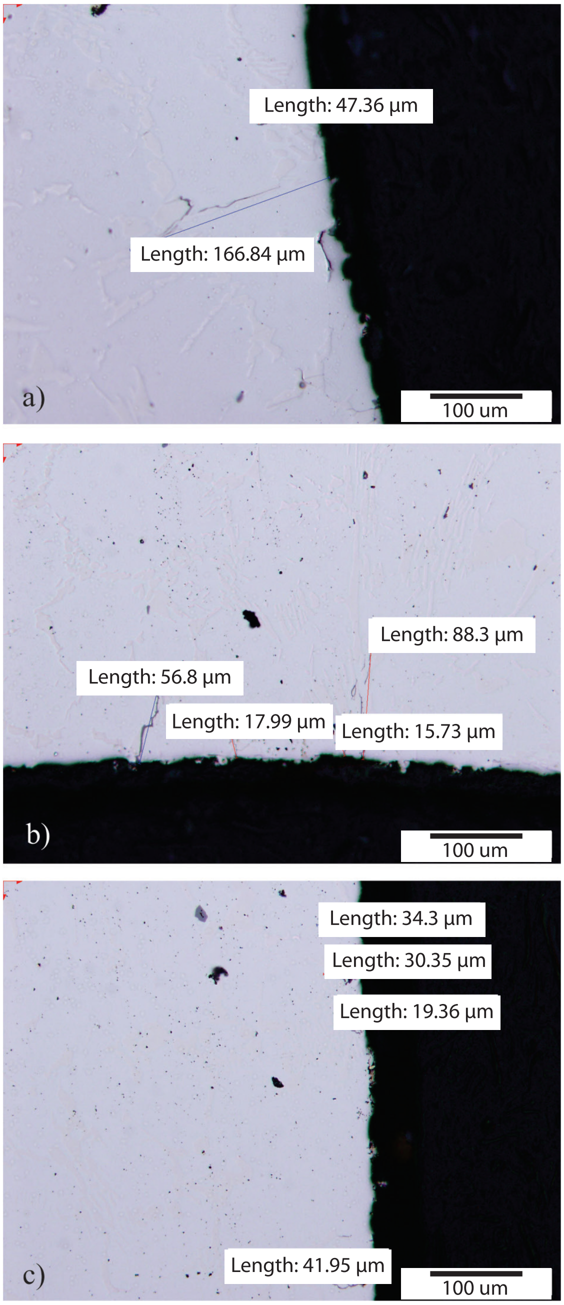

Figure 10: *Crack lengths: t = 15 s, air cooling (a), t = 60 s, air cooling (b), t = 60 s, water cooling (a).*

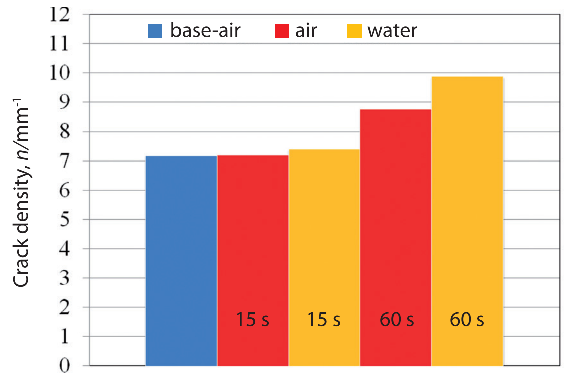

Figure 11: *Crack density.*

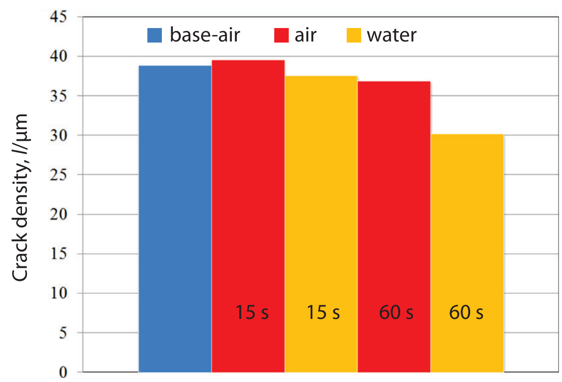

Figure 12: *Average cracks length.*

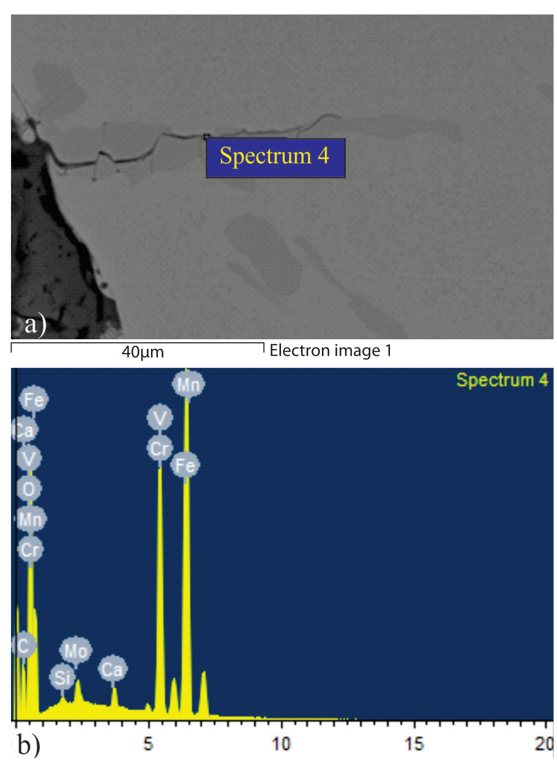

Figure 13: *SEM micrographs of the investigated crack (a), and the related EDS spectra (b).*

Conclusion

Two thermal fatigue tests for the estimation of thermal fatigue resistance of work rolls were developed. They are based on computer guided heating and cooling of the specimen using Gleeble 1500D thermo-mechanical simulator. The specimen geometry enables the achievement of high temperature gradients. These tests will contribute to better understanding of crack nucleation and their growth during the usual hot rolling conditions, as well as for the case of rolling mill stalls.

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