THERMAL CRACK PROPAGATION DURING HOT ROLLING AND ITS INFLUENCE ON CAST IRON WORK ROLL DEGRADATION

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Abstract

Indefinite chill cast iron rolls are commonly used in the finishing stands in hot strip rolling mills. Due to characteristic rolling conditions in these stands and due to a hypoeutectic ledeburitic microstructure with graphite inclusions in the working layer, the mechanism of thermo-mechanical wear is different from earlier stands. Some research has been done on thermal fatigue crack formation and propagation in various alloys used for working layers in rolls. This research focuses on the impact of formation and propagation of extremely long cracks in some enhanced grades along with possible influence of the amount of added special carbide forming elements in these grades. These long cracks propagate from the surface of the roll inwards and may lead to bigger problems during rolling campaigns when not dealt with properly. Previous work also suggests that the ledeburitic network microstructure is indicative of the formation of thermal fatigue cracking on the surface of the roll. We analyzed the as-is microstructure of the roll's surface after a campaign using silicon replicas to assess the crack mesh created on the surface during rolling. The results of this work highlight the combined influence of microstructure and thermo-mechanical fatigue in work roll degradation.

Keywords: Indefinite chill cast iron, work rolls, thermal fatigue, crack propagation, roll surface degradation

1. INTRODUCTION

Rolling conditions on the rear finishing stands in continuous or semi continuous hot strip mills are more severe in comparison to front and roughing stands. Rolling speed on the presented area is increased to maximum due to the final plastic deformation of the rolled metal and temperature of the strip is lower in comparison to earlier stands. This conditions are the cause of the high thermo-mechanical load present on the work roll's surface. Taking into the account also the final quality of the rolled metal, work rolls material is obliged to have perfect anti-sticking properties too. The mottled hypoeutectic Ni-hard material combining white cast iron microstructure along with free graphite flakes enables good anti-sticking properties despite the decrease in wear resistance due to the softer graphite phase [1]. To provide sufficient lubrication for lowering friction and to stop the thermal fatigue crack propagation, nodular shape of graphite is essential. Besides graphite phase, ICDP or Ni-hard microstructure consist of a high cementite ratio (more than 30 %), mainly in the form of ledeburite with a matrix consisted of bainite and martensite [2]. Due to a relatively low hardness of the cementite, modification of standard ICDP roll grade is performed in order to increase wear resistance during hot rolling process in the finishing stands.

To increase the service life of the work rolls is becoming a more and more demanding task for every roll producer. Several authors concluded in their studies that modification of the ICDP roll grade, using the special carbide forming elements (SCFE), such as tungsten, titanium, vanadium and niobium, enables precipitation of eutectic MC-type carbides inside the matrix [3, 4, 5]. This type of carbides are known for their hardness, small size and dispersed distribution. Two different technologies of adding SCFE into the standard ICDP alloy exist: the first method is based on addition of existing carbides directly into the melt and the second method is based on alloying. A sufficient amount of SCFE results in a eutectic reaction where eutectic MC-type carbides are precipitated from the melt. With adjusting melt inoculation, a more nodular graphite form is achieved. Unlike the interdendritic graphite phase, found in standard ICDP, nodular shape of graphite precipitated in modified ICDP reduces and stops the crack propagation.

During the rolling process, work rolls are thermo-mechanically loaded. Thermal loadings on the work rolls result in rapid heat transfer from the preheated rolled metal to the work roll surface layer material. A small thermal stress field may also appear in the area between the work and the back-up roll due to friction. Schröder [6] studied the heat transfer from the rolled metal to the work roll. Results show that the temperatures of work rolls vary from 600 °C to 100 °C during one revolution of the roll. The highest temperature represents the moment when the work roll is in contact with the rolled metal, while the lowest one is valid to the roll cooling area. Belzunce et al. [7] concluded that with the quick change of temperature during the rolling process, small fire cracks can appear on the work roll surface. In connection with mechanical loadings, especially in the contact area between the work and the back-up roll, the appearance of fire cracks could lead to roll surface degradation [8]. Different types of failures can be observed on work rolls during their exploitation. A comprehensive investigation among them is published in [9]. All work roll failures have different kinds of origins related either to roll manufacturer or specific conditions in the rolling mill.

2. EXPERIMENTAL TESTING

Standard and modified ICDP work roll surface layer materials were used for experimental investigation. The difference between them is in the content of different carbide forming alloying elements. Chemical composition of the analyzed material was measured using a spark ignition spectrometer from the producer Spectrolab. Mean results are presented in **Table 1**. The standard ICDP grade is labelled CIN and the alloy labeled CINA represent the modified ICDP grade with SCFE ratio above 1 wt. %.

Table 1 Chemical composition of the investigated ICDP materials

Roll Grade	Element wt. %					
	C	Si	Cr	Ni	V + Nb + Ti + W	Fe
CIN	2.8 - 3.4	0.80 - 1.6	1.75	4.46	0	Bal.
CINA	2.8 - 3.4	0.80 - 1.6	1.58	4.37	> 1	Bal.

All specimens that were needed for present investigation were cut out from the roll shell segment after heat treatment by using the abrasive water blast technology, in order to prevent the formation of heat affected zones because of friction upon cutting.

Metallographic analysis was performed on cross sectional samples throughout the entire working layer material. Specimens were prepared with a standard metallographic procedure of grinding and polishing. A 2 % Nital was used to etch the samples in order to reveal the microstructure. Samples were finally inspected by using an Olympus BX51M optical microscope, equipped with an Olympus DP-12 camera. For evaluation of the microstructure a JMicroVision v.1.2.7 software was used.

To investigate the thermal fatigue cracking phenomenon of the work roll surface layer material, a thermo - mechanical simulator Gleeble 1500D was used [10]. Tests were performed at 1000 cycles in the temperature range between room temperature and 600 °C. Each cycle was composed of five phases: resistance heating up to 600 °C (2 s), holding on the prescribed temperature (0.2 s), water cooling (0.5 s), air cooling (0.5 s) and emptying the specimen by using air pressure (0.2 s). The performed thermal fatigue cycle was created in order to simulate specific conditions that the surface layer of the work roll is subjected during the hot rolling process.

To compare the results from the experiment with the real surface of the roll after the exploitation, a case study of work roll spalling was performed.

3. RESULTS AND DISCUSSION

3.1. Metallographic analysis

Figure 1 shows optical microphotographs of standard ICDP (a, b) and modified ICDP (c, d) roll grade. It is evident that nodular type graphite flakes are precipitated in the modified ICDP material (form V to VI acc. to ISO 945-1-2009). In the case of standard ICDP roll grade, a chunkier type of graphite could be detected (form IV acc. to ISO 945-1-2009). Both matrix microstructures consist of bainite and martensite.

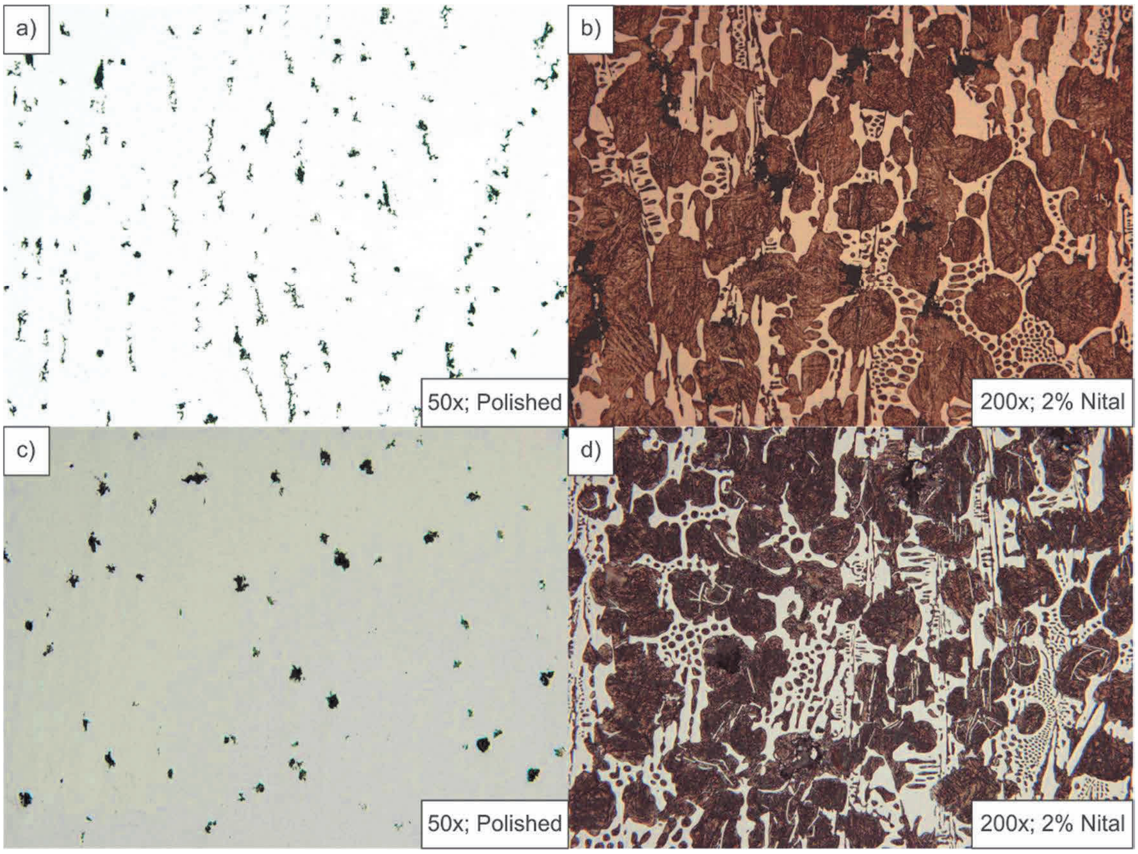

Figure 1 Comparison between microstructures; a), b) standard ICDP - CIN, 40 mm in depth of the specimen; c), d) modified ICDP - CINA, 40 mm in depth of the specimen

We can observe that by the alloying the standard ICDP roll grade with SCFE, graphite ratio decreases in favor of cementite formation. With the quantitative metallographic analysis of both specimens, we can prove this assumption, see **Table 2**.

Table 2 Quantitative metallographic analysis of the both specimens

Roll Grade	Graphite ratio %		Carbide ratio %	
	Edge	40 mm	Edge	40 mm
CIN	1.23	2.35	30	26
CINA	0.94	1.22	31	29

Values from the **Table 2** show that graphite ratio increases in the way from outer edge toward the center while carbide ratio in the same direction decreases. Such results are expected for both ICDP roll grades.

3.2. Thermal fatigue inspection

Thermal fatigue cracks appear on the entire investigated surface area of the specimen and propagate perpendicularly inside the specimen. Carbides and graphite appear to be the main source of crack initiation. Carbides present a different temperature expansion coefficient and lower ductility in comparison to the matrix material. They have a poor response to tensile stresses generated during continuous heating and cooling of the roll or the specimen surface area. Unlike carbides, graphite is significantly softer than the base material and can cause a large notch effect if its morphology is not nodular. This may be the reason why some cracks initiate inside the material as opposed to the surface. **Figure 2** depicts fatigue cracks propagated during testing in both analyzed grades.

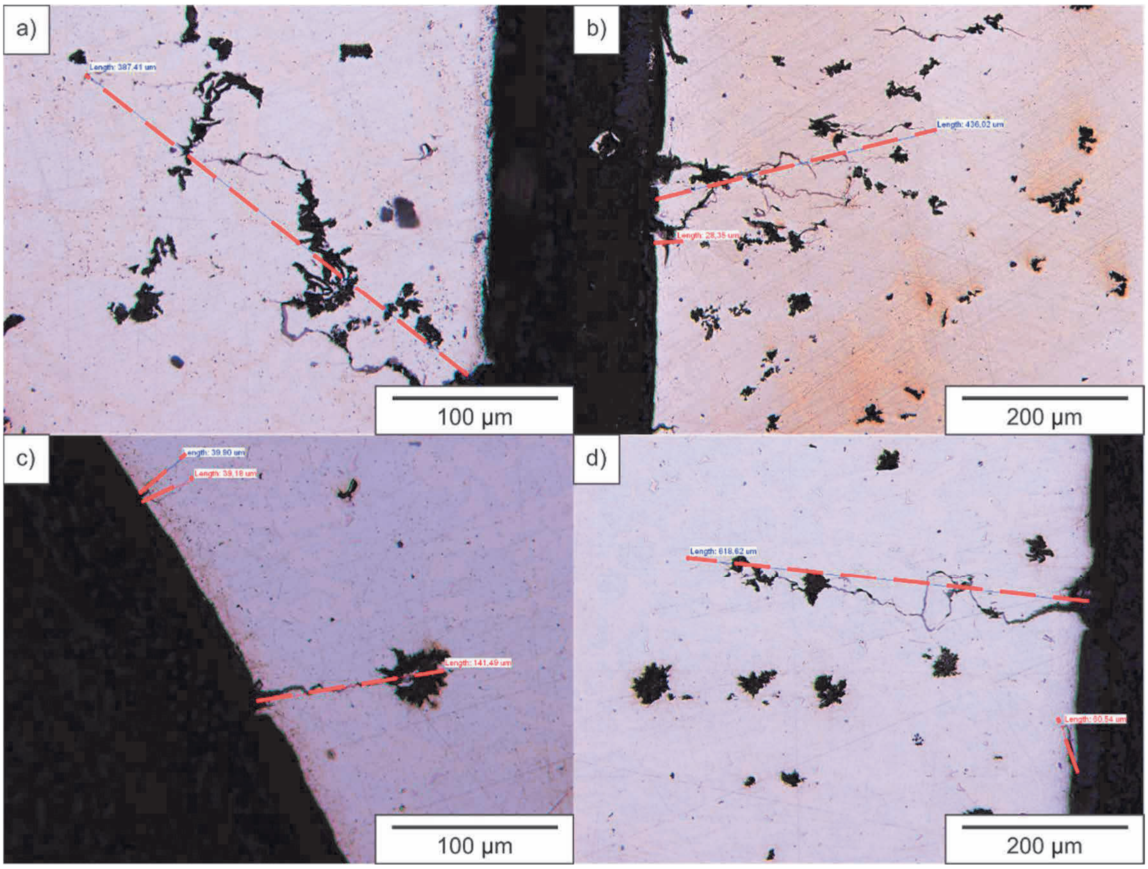

Figure 2 Optical microphotographs of cracks formed during thermal fatigue investigation; a), b) standard ICDP - CIN; c), d) modified ICDP - CINA

Results of the thermal fatigue investigation shows that cracks propagate mainly through ledeburite, mostly along the carbide-matrix boundaries. These cracks are transcrystalline in origin although in some rare cases intercrystalline cracks were also visible along grain boundaries. Sometimes crack propagation is halted when the crack reaches a graphite flake or nodule. This is more pronounced when nodular graphite is present in the matrix. If the shape of graphite is chunky or unidirectionally oriented, cracks may propagate alongside the graphite flake and continuously grow inside the material and can also easily change the direction.

Characteristics of the crack for both investigated materials is presented in **Table 3**. An improvement regarding thermal fatigue resistance is visible for the modified ICDP - CINA roll grade. In comparison to the standard ICDP - CIN material, modified ICDP shows the reduction of the total number and density of cracks. We can assume that with the alloying the melt with SCFE material matrix is enhanced and can withstand crack initiation and later also propagation.

Table 3 Characteristics of the crack for the CIN and CINA roll grade

Specimen	CIN	CINA
Number of cracks	210	143
Average length (μm)	88	145
Max. length (μm)	685	905
Total length (μm)	18490	20766
Crack density (n/mm)	7.5	5.1

Despite the reduced number and density of cracks, modified ICDP - CINA shows the highest number of extremely long cracks (longer than 500 μm). This could be the result of a lower graphite ratio in comparison to the standard ICDP - CIN roll grade. Formation of these long cracks during the rolling process cause a higher grind rate in the roll shop and consequently the loss of roll efficiency measured in tons rolled per millimeter of the working layer t/mm. If the roll is not properly prepared before the installation in the rolling stand, these long cracks can easily propagate inside the roll and may cause spalling. Mentioned properties of the CINA roll grade can make a roll more sensitive and require the roll shop manager to completely remove the cracks from the surface. What is more, if the rolling mill is not technically improved in terms of cooling, entry dimensions, speed and controlled temperature of the rolled metal then the enhanced ICDP material should not be used because of extremely long cracks phenomenon.

4. CASE STUDY

As it was already mentioned, CINA roll grade is more sensitive and with the improper rolling conditions on the rolling mill can quickly get spalled. **Figure 3a**, presents the silicon replica of the surface layer of the work roll. We can observe a network of the cracks presented on the surface of the roll. These cracks are so small that they cannot be detected by penetrant test, magneto-flux or eddy-current EC. That is the reason that the roll must be grinded properly to remove the cracks from the surface.

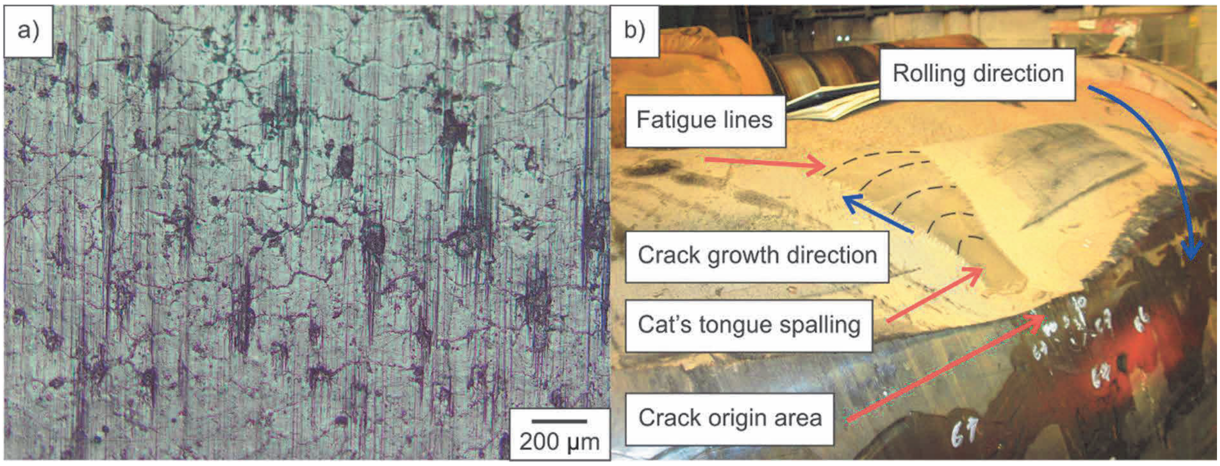

Figure 3 Analyses of CINA work roll surface; a) a silicon replica of the CINA roll surface after exploitation; b) appearance of the cat's tongue on the spalled surface of the CINA work roll.

If the crack is not removed from the surface and that kind of roll continuously operates in rolling mill, it can happen that that the roll will spall due to the high contact stresses, see **Figure 3b**. In the first stage a crack is presented or newly formed in an area of local overload, at or near barrel surface. Such a crack is usually oriented parallel to the roll axis. In the next phase a fatigue cat's tongue like fracture band propagates progressively in a circumferential direction. The direction of propagation is opposite to the roll rotation. Propagation develops within the working surface of the roll, gradually increasing in depth and width followed by a large surface spall normally on the bonding area between the working layer and the core of the roll [10].

5. CONCLUSION

Thermal crack propagation during hot rolling and its influence on cast iron work roll degradation is presented in this paper. Experimental results show that with the addition of the special carbide forming elements SCFE number and density of cracks decreases. On the other hand, it is visible that the number of extremely long cracks increases in the case of modified ICDP - CINA material. Higher SCFE addition inhibits graphitization in favor of the cementite phase. Free graphite flakes, commonly interdendritic, can be seen in standard ICDP - CIN roll material, while graphite in modified ICDP - CINA roll grade is more nodular. Sometimes crack propagation is halted when the crack reaches a graphite flake or nodule. This is more pronounced when nodular graphite is present in the matrix. If the shape of graphite is chunky or unidirectionally oriented, cracks may propagate alongside the graphite flake and continuously grow inside the material.

Presented study is comparable to the results of service life of rolls from different rolling mills. Case study shows that if the rolling mill is not technically improved and workers at roll shops do not grind the roll surface properly than modified ICDP - CINA material can get easily spalled. In this case, standard ICDP - CIN material is more suitable due to its high graphite ratio and robust properties.

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