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FATIGUE CRACK GROWTH AND FRACTURE MECHANICS ANALYSIS OF A WORKING ROLL SURFACE LAYER MATERIAL

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Fatigue crack growth and fracture mechanics analysis of a working roll surface layer material is presented in this paper. The research is done on a hot strip mill working roll where High Chromium Steel is used for roll's shell material. To obtain corresponding parameters, a rectangular single edge notched bend specimens – SENB, according to standard BS 7448, were used. The fatigue crack growth analysis was done on a resonant testing machine with use of special crack gauges, while for fracture mechanics parameters the electro–mechanical testing machine was used.

Key words: fracture mechanics, fatigue crack growth, rolling, high chromium steel

INTRODUCTION

Rolling is a metal forming process where metal is drawn into the rolling gap by using a pair of working rolls. Attaining the required plastic deformation of rolled metal is the main goal of a rolling process. In order to achieve this condition, working rolls must be manufactured and thermally treated in such a way that they will operate a certain service life under given loading condition [1, 2]. A variety of working rolls according to the dimensions, design and material properties could be chosen for different types of rolling stands. Working rolls which operate at the beginning of a rolling process in a hot strip mill, at reversible roughing 4 – high stands, are double layered. The 4 – high stand is composed of two working and two back up rolls. A carbide based cast steel material High Chromium Steel is used for hard and wear resistant working layer cast by using special centrifugal casting machine, while for the core a classic gravity casting procedure as a combination of perlitic – feritic nodular graphite cast iron is used to assure the required toughness of roll's core.

SPECIFICS OF ROLLS LOADING

Due to operating conditions in 4 – high stands, rolls are thermo-mechanically loaded. When studying thermo-mechanical loads of rolls during one revolution, two types of stress and strain field could be considered in the contact. Stresses in the area between working and back up roll could describe the Hertzian contact theory between two elastic circle bodies and in the area between working roll and rolled metal, which are widespread through the larger contact field. Thermal loadings on working rolls result in rapid heat transfer from rolled metal to working roll in the time when contact between them is established. After the contact is established, surface temperature of the working roll falls quickly, because of water cooling. Schröder [3] investigated the temperature distribution during one revolution of the working roll. He showed that temperature changes from 600 °C to around 100 °C. Similar Belzunce et al. [4] concluded that with the rapid change of temperature during rolling process, small fire cracks could appear on working roll surface. In connection with mechanical loadings especially at the contact between working and back up roll the appearance of fire cracks could lead to roll's surface failure and breakage.

Different types of failures could be noticed on working rolls during their exploitation. A comprehensive investigation among them is published in [5]. Due to high contact stresses between working and back up roll pressure cracks could appear near or on the working roll surface. In the next phase a fatigue fracture band propagates in the surface. Such fractures are called "Cat's Tongue Spalls", see Figure 1.

All working roll failures have different kinds of origins related either to roll manufacture or specific rolling conditions in the mill. Podgornik et al. [6] investigated different machining parameters and the influence of heat treatment on residual stress field and wear of double layer cast rolls. Their conclusions show that with

Figure 1 A Cat's Tongue Spall visible on working roll surface layer

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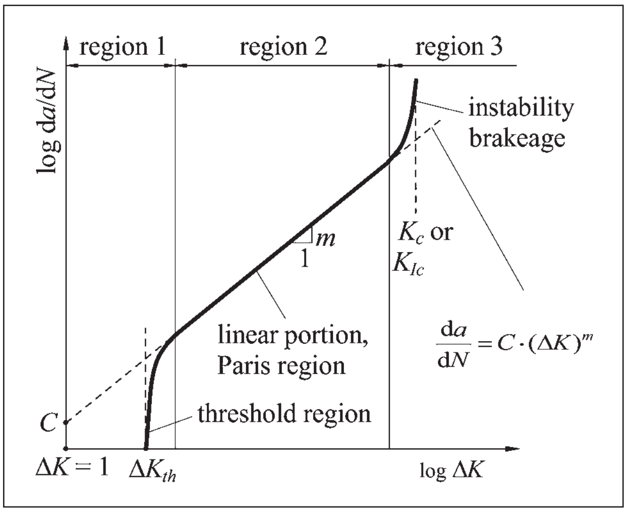

Figure 2 Typical fatigue crack growth curve with three regions

incorrect production phase a high tensile residual stresses could be observed on working rolls surface layer. Simunovic et al. [7] exposed that with inappropriate surface roughness the possibility of surface cracks appearance increases. In connection with conditions in rolling stands, tensile residual stresses and surface cracks could be fatal regarding the structural integrity of working rolls.

EXPERIMENTAL TESTING

Theoretical background

To understand the structural integrity of working roll, parameters of the fracture mechanics such as K_{Ic} – plane strain fracture toughness of the material, should be known and moreover, fatigue crack growth accordance with the number of working cycles should be obtained. In many structural components subjected to cyclic loadings, critical growth often occurs due to fatigue until critical crack size is reached causing fracture [8]. Three regions could be observed when plotting the typical fatigue crack growth curve, see Figure 2.

Region 1 indicates the threshold value ΔK_{th}, below which there is no crack growth. In this region, microstructure, mean stress and environment mainly control the crack growth. A linear relationship between fatigue crack growth rate log *da/dN* and applied stress intensity factor range log ΔK also known as Paris law [8] represented in equation (1) could be observed in region 2 and corresponds to stable macroscopic crack growth.

$$\frac{da}{dN} = C\cdot(\Delta K)^m \tag{1}$$

In region 3 the fatigue crack growth rates are very high as they approach instability. This region is primarily controlled by $K_{Ic.}$

Experimental procedure

Determination of fracture mechanics parameters and fatigue crack growth curve was done at room temperature which is related to the condition on the contact field between working and back up roll. All specimens SENB according to standard BS 7448 [9] were cut out of the working roll shell, by using abrasive water blast technology, and the wire erosion procedure was used for creating a notch. Therefore it is assumed that specimens have similar characteristics as the working roll. The width of the specimen W = 16 mm and its thickness B = 8 mm.

Before experimental testing, chemical composition of HCS was determined by using an emission spectrometer Spectrolab, see Table 1, while mechanical material properties are presented in Table 2. Figure 3 shows a microstructure of HCS specimen etched with Vilella at 1000 x magnification before and after special heat treatment by using the Olympus DP 12 camera in the Olympus BX 51 M light microscope.

Heat treatment of working rolls is composed of various quenching and tempering processes. From Figure 3 it is evident that with heat treatment, beside eutectic carbides M_7C_3 segregated along grain boundaries, also secondary $M_{23}C_6$ chromium carbides participate in the matrix. In combination with other carbides, chromium car-

Table 1 **Chemical composition of HCS determined with emission spectrometer**

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Fe
%	1,75	0,68	0,74	0,027	0,037	11,55	1,94	1,13	0,14	0,25	rest

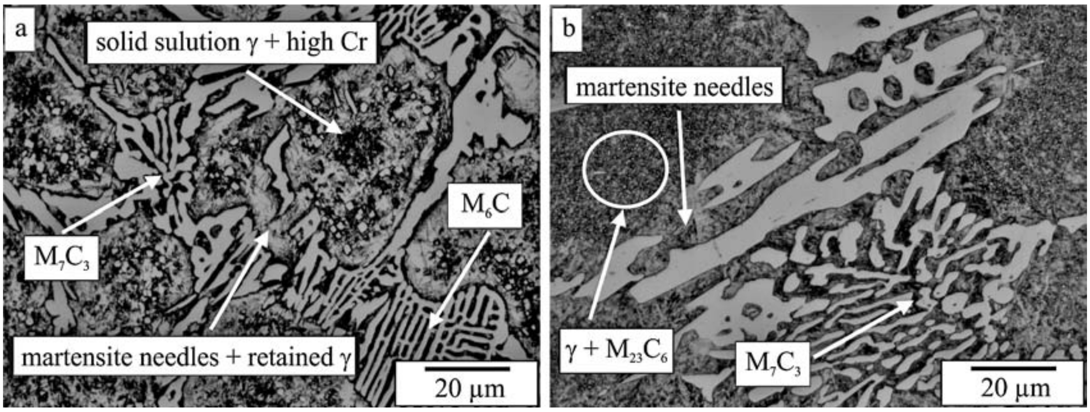

Figure 3 Microstructure of High Chromium Steel – HCS; a) before heat treatment, b) after heat treatment

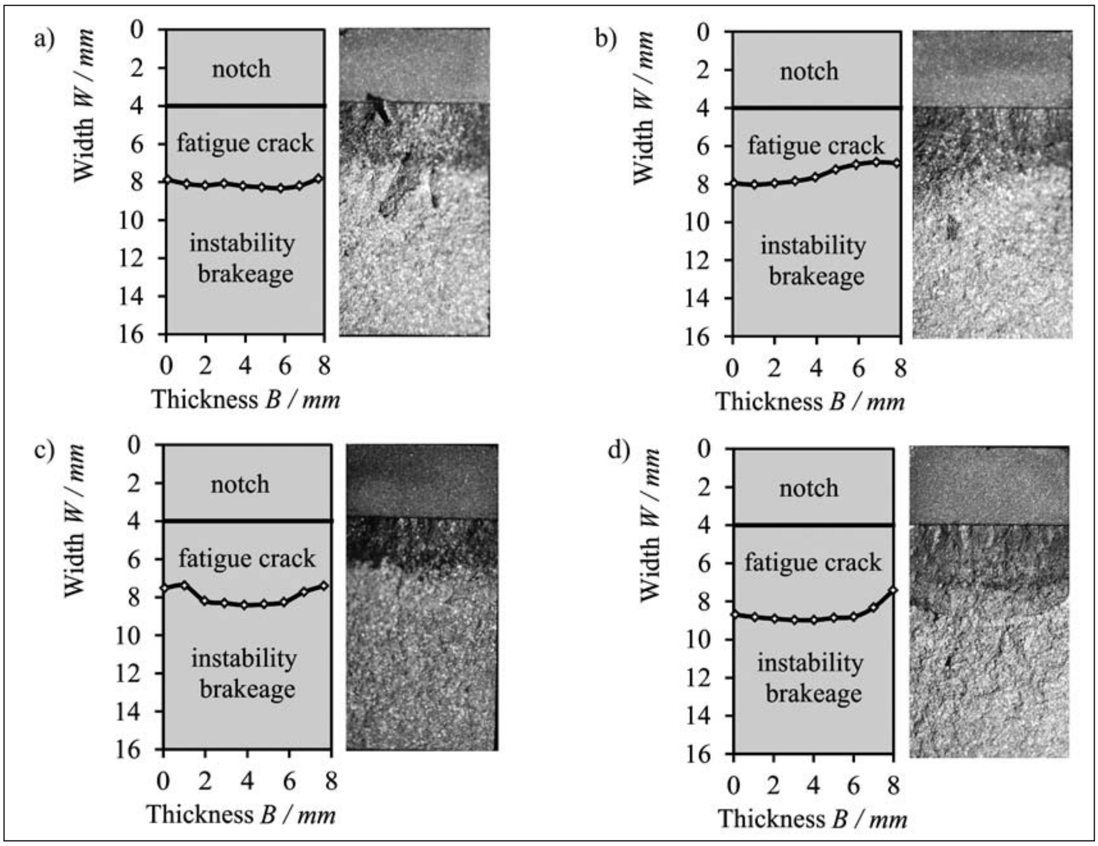

Figure 4 Fatigue crack length; a) Specimen 1, b) Specimen 2, c) Specimen 3, d) Specimen 4

bides contribute to the appropriate hardness, tensile/compression strength and wear resistance of the material.

Fracture mechanics testing was performed at room temperature, on the electro–mechanical testing machine SCHENK TREBEL RM 100. Crack mouth opening displacement was registered by the special extensometer KLIP – GAGE DD1, the measuring accuracy of which is ± 0,001 mm. After testing, K_{Ic} was determined according to standard plane strain conditions described in [9]. The device for a crack increment registration FRACTOMAT was used for determination of fatigue crack growth curve. A special foil gauge RMF A – 5 was applied on a specimen to register the change in electrical resistance.

Table 2 **Mechanical material properties at room temperature**

Tensile Strength R_m / MPa	Compressive Strength σ_c / MPa	E / MPa	ν
930	2345	213 400	0,288

RESULTS

A fatigue crack length needed for determination K_{Ic} factor is presented in Figure 4. Surfaces of the specimens show that a brittle fracture is presented. In Figure 4b and Figure 4c some unusual curves of fatigue crack growth through the specimen thickness could be observed. This probably happened because HCS is a carbide based material and when crack hits carbide, it could change the direction of propagation. Values of K_{Ic} for each specimen represented in Figure 4 are specified in Table 3.

Table 3 **K_{Ic} values for each specimen**

	1	2	3	4
K_{Ic} / MPa $\sqrt{m}$	34,36	24,96	26,71	27,24

The Fatigue crack growth curve for HCS is presented in Figure 5.

Material parameters ΔK_{th} and K_{Ic} could be observed in Figure 5. In the region where stable crack growth is detected factors C and m, needed for Paris law equation,

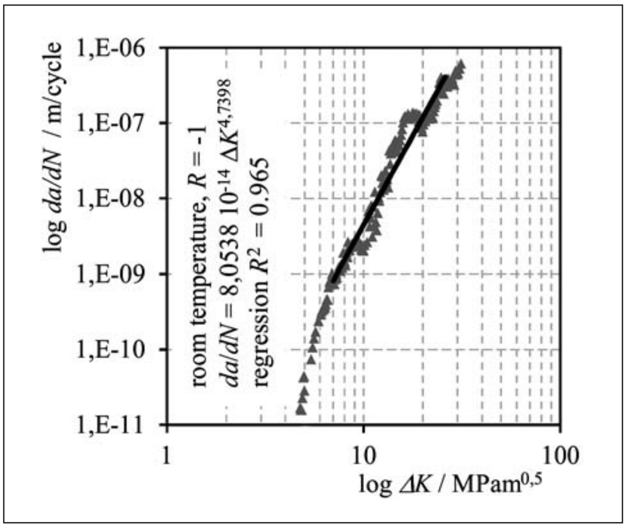

Figure 5 log da/dN – log ΔK dependency diagram for HCS

could be determined. Values of coefficients and ΔK_{th} are given in Table 4.

Table 4 **Parameters *C, m* and ΔK_{th}**

ΔK_{th} $(MPa\sqrt{m})$	$C\left[\frac{m/cycle}{(MPa\sqrt{m})}\right]$	m
4,84	8,0538 10^{-14}	4,7398

A small difference between ΔK_{th} and K_{Ic} could be observed, which reflects in low service life of working rolls with crack presence.

CONCLUSION

Fracture mechanics analysis and fatigue crack growth of a working roll surface layer material High Chromium Steel is presented in this article. All experimental investigation was performed as it is described in standard BS 7448 [9]. Before experimental testing a microstructure of HCS before and after heat treatment is presented.

Results of the fracture mechanics analysis shows that when a crack is presented, a small load is needed for rupture and brittle fracture, which is proven with fracture surfaces presented in Figure 4 and with low values of K_{Ic}. After fracture mechanics analysis, the fatigue crack growth was determined. Results of the investigation are presented in log *da/dN* – log ΔK diagram, Figure 5. ΔK_{th} coefficient could be observed from the diagram. There is a small difference between ΔK_{th} and K_{Ic} which reflects in low service life of roll with crack presence.

Results presented in this study will serve as a basis for more comprehensive investigation related to roll's microstructure influence on crack propagation.

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