IMPROVEMENT OF WORK ROLL SERVICE LIFE BY MICROSTRUCTURE SIMULATION

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Abstract

The work roll surface in hot rolling mills suffers combined heat and mechanical load. The surface degradation leads to the formation of crack networks. The current research describes a thermal fatigue similar to the governing degradation mechanism, which causes the cracks formation perpendicular to surface. This paper describes the additional effect of cyclic thermal loads - the cause of parallel-to-surface cracks formation within long and thin carbides which is prone to forming inside HiCr steel.

The cracks formation is investigated by both a thermal and a structure FEA. These analyses are conducted with a special finite element model which has a steel microstructure. The model is exposed to a thermal load at the end of the rolling gap. The result - the heterogeneous thermal field is applied like a BC for the structure analysis.

The results are presented by a histogram of relative frequency of the first principal stress value, for each microstructure portion separately. The distribution of the first principal stress within the matrix shows a compressive stress state, which was anticipated. The distribution of the first principal stress within the carbide portion shows a tensile stress state, which was unexpected.

This unexpected behavior is explained by a different thermal expansion coefficient of each portion of the microstructure. The matrix with a higher thermal expansion coefficient expands more rapidly than carbides which are pressed from a surrounding matrix which forces them to lengthen, and which, in turn, cause tensile stress within carbides. Based on the comparison with a microstructure typical to HiCr iron, the recommendation for a more durable and resistant microstructure structure are stated and explained.

Keywords: Work rolls, hot rolling, microstructure, crack, formation, thermal fatigue

1. INTRODUCTION

The work roll surface in hot rolling mills suffers from a combined heat and mechanical load. The load leads to the degradation of the work rolls' surface. This degradation could result in several ways, but mainly to the formation of crack networks on the surface. The crack networks drastically reduce the quality of a steel strip and can decrease the service life of a work roll. The existing research describes a thermal fatigue similar to the governing degradation mechanism, which causes perpendicular to-surface crack formation. Besides perpendicular-to-surface cracks we can observe other type of cracks - inclined-to-surface and parallel-to-surface cracks.

It is generally known that the origin of the inclined-to-surface cracks is contact fatigue, but the origin of the parallel-to-surface cracks is unclear. Mostly, they appear inside M_7C_3 carbides, see **Fig. 1**, the density of the parallel-to-surface cracks are highest in a High Chromium iron (HiCr iron) [1.2]. This type of material was widely replaced by HiCr steel with less content of Carbone and a different microstructure. The work roll with this type of material has a higher service life [3] and this improvement could be explained by the microstructure numerical simulation using FEM.

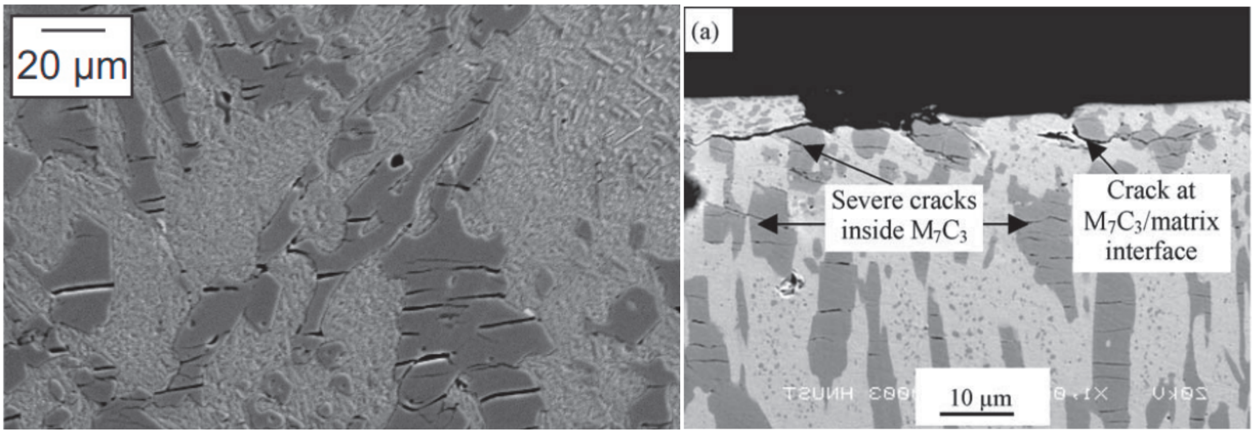

Fig. 1 The parallel-to-surface cracks inside M_7C_3 carbides [1.2]

2. NUMERICAL MODEL FOR SIMULATION OF MICROSTRUCTURE

The cracks formation is investigated by both a thermal and a structure finite element analysis. These analyses are conducted with the special finite element model which has a steel microstructure. The model is based on Voronoi tessellation of plane into Voronoi cells. The numerical model represents 200 × 200 μm wide 2D area closed to the work roll surface. The cracks' initialization happens in an area of about the same range because of the highest temperature gradient. These cells are separated into two groups. Each group represent one portion of the steel microstructure - the matrix and the carbide. Each Voronoi cell group has different material properties. Based on the user requirements, a dedicated algorithm performs the cell separation. The algorithm has two main sear directives - for the HiCr iron-like material and for the HiCr steel-like material. The first directive produces long, thin groups of carbides along vertical lines, see **Fig. 2** (on the left). The second directive produces a network-like distribution of carbides, see **Fig. 2** (on the right). These geometries are transferred into ANSYS, where FEA is conducted.

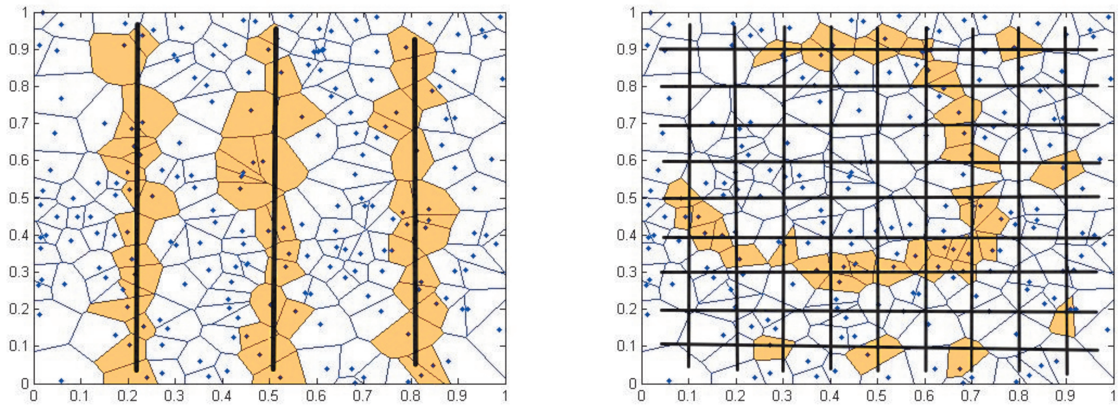

Fig. 2 The algorithm for the generation of HiCr iron (on the left) and steel (on the right) like microstructure. The plane is randomly divided in Voronoi cells which are categorized into two groups - for matrix and for carbides (brown colour). The automatic selection goes along fictitious lines until the stop criterion is reached

Firstly, the static thermal analysis is conducted. The model is exposed to a thermal load at the end of the rolling gap where the highest thermal load during revolution of the work roll is. The thermal load is based on the previous experimental work conducted by the Heat Transfer and Fluid Flow Laboratory [4] and the area close to the work roll surface could be characterized by a linear equation, see **Fig. 3**. The result - the heterogeneous thermal field is applied like a boundary condition for the structure analysis. No additional loads are used.

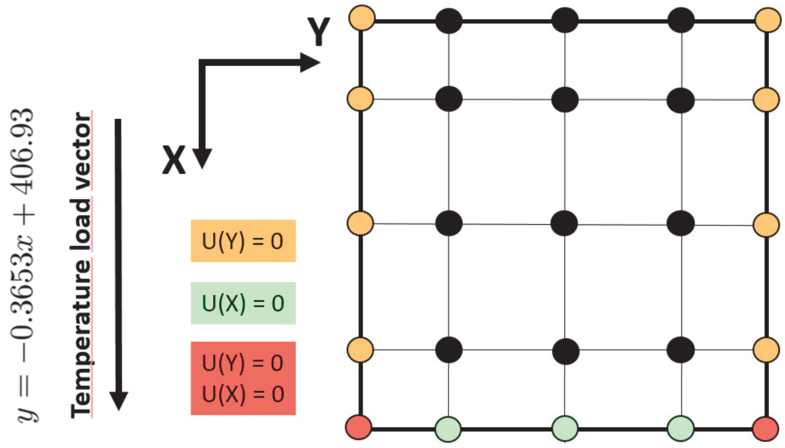

Fig. 3 The description of the boundary condition was used for the presented simulations. The nodes attached to the bottom horizontal line has zero displacement along X axis, the outer vertical lines have zero displacement along Y axis. For the thermal analysis, the boundary conditions are similar, zero displacement are substituted by zero heat flux

Two different microstructures were generated for this paper. The first generated microstructure represents HiCr steel, see **Fig. 4**. The second generated microstructure represents HiCr iron, see **Fig. 5**. Each microstructure has the same material models properties, see **0Table 1**.

Table 1 Material properties used for the presented simulations [5]5,6,7,8]:

Material property	**Matrix (Martensite)**	**Carbides (Cr_7C_3)**
Yield strength	900 MPa	[-]
Young's modulus	206 GPa	289 GPa
Poisson ratio	0.25	0.31
Density	7815 kg · m^{-3}	7050 kg · m^{-3}
Conductivity	22 W · m^{-1} · K^{-1}	18 W · m^{-1} · K^{-1}
Specific heat	520 J · kg^{-1} · K^{-1}	480 J · kg^{-1} · K^{-1}
Thermal expansion coefficient	13 · 10^{-6} · K^{-1}	12,5 · 10^{-6} · K^{-1}

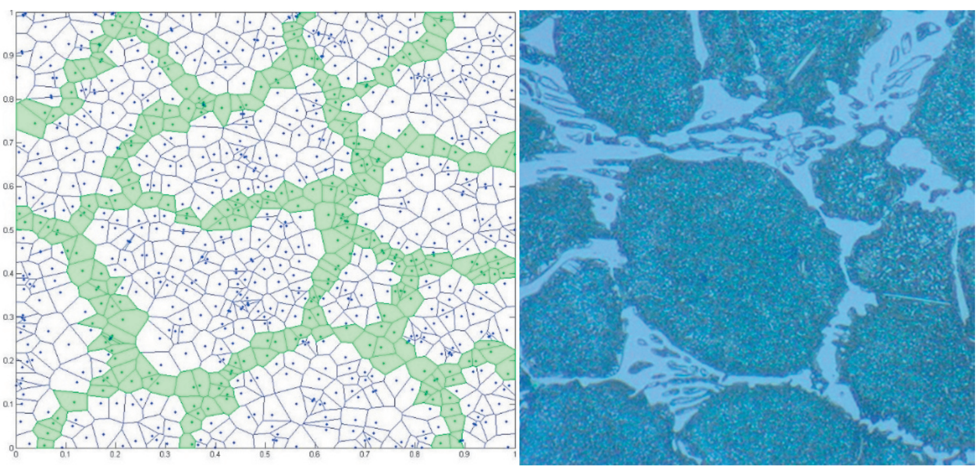

Fig. 4 The example of generated HiCr steel like microstructure (on the left side) with real material structure (on the right) comparison [9]

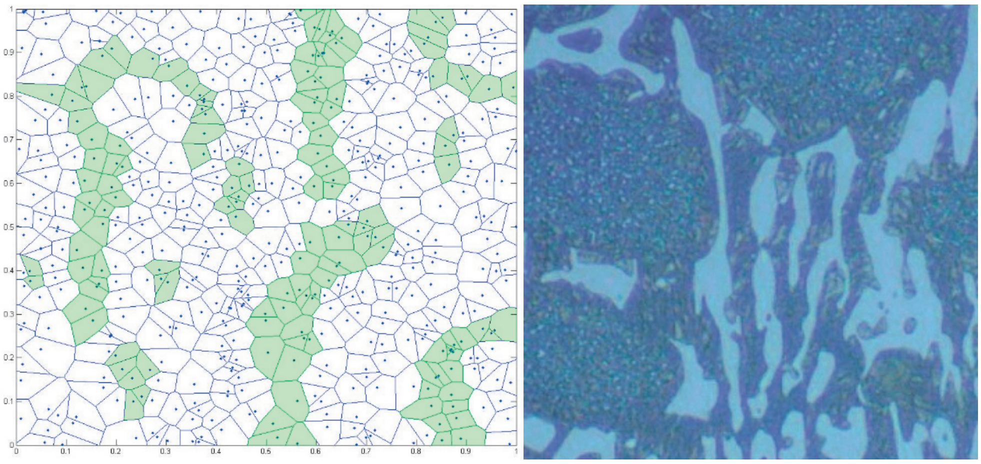

Fig. 5 The example of generated HiCr iron like microstructure (on the left side) with real material structure (on the right) comparison [10]

The bilinear elastic-plastic material model was used for Voronoi cells which represents matrix. The pure elastic model was used for carbides because of information insufficiency about carbides elastic-plastic behavior. **Table 1** contains all used material properties.

3. RESULTS

The results are presented in form of relative frequency histograms of 1st principal stress. This method was used in [11] and it tries to overcome the stochastic nature of the described problem, it gives us an idea about the predominant stress and its distribution.

In the case of the HiCr steel-like microstructure, the matrix is exposed to compressive stress. The values are concentrated around -50 MPa. The distribution could be characterized as Gaussian/normal, see **Fig. 6** (on the left side). The carbides are exposed to combined tensile and compressive stress. The distribution is not uniform and a significant portion could be found around 200 MPa, see **Fig. 6** (on the right side).

In the case of the HiCr iron-like microstructure, the matrix is also exposed to compressive stress load. The values are concentrated around -20 MPa. The distribution could be characterized like logarithmic-normal, see **Fig. 7** (on the left). The carbides are mainly exposed to a tensile load. The distribution is disproportional and the significant portion is concentrated around 200 MPa.

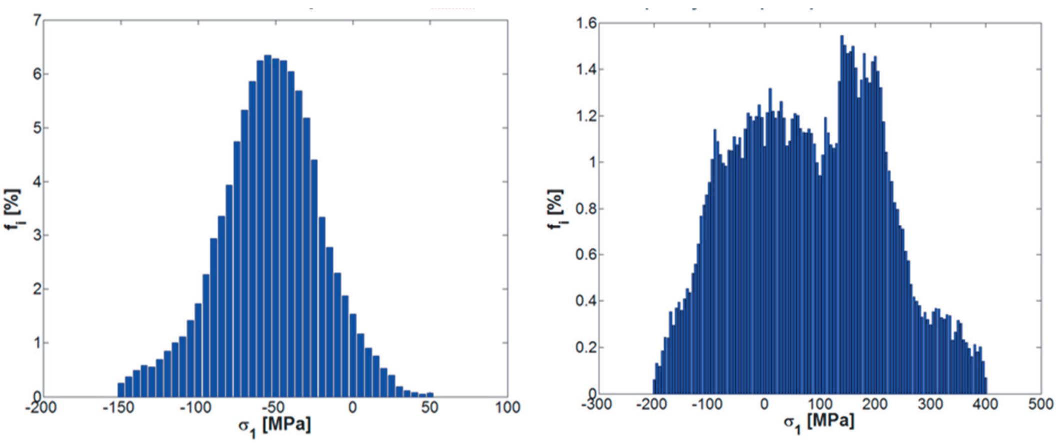

Fig. 6 The relative frequency distribution of 1st principal stress for the matrix (on the left) compared to 1st principal stress distribution for the Cr_7C_3 carbides (on the right) taken from HiCr steel microstructure

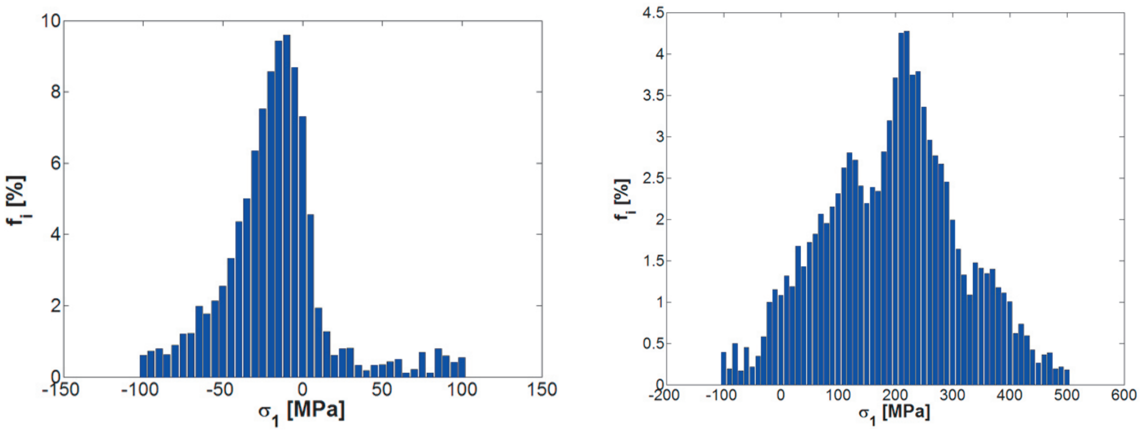

Fig. 7 The relative frequency distribution of 1st principal stress for the matrix (on the left) compared to 1st principal stress distribution from the Cr_7C_3 carbides (on the right) taken from HiCr iron microstructure

4. DISCUSION

The matrix is under compressive stress in both studies. This compressive stress regime is caused by heat related expansion of the matrix. The HiCr steel matrix has higher compressive stress values which could be explained by a continuous carbides network which limits a deformation of the matrix.

The simulations showed surprising behaviour of carbides. The HiCr iron carbides were exposed mainly to tensile stress and the HiCr steel carbides were exposed to combined compressive and tensile stress which was dominant.

This behaviour could be explained if we focus on the shape of carbides and if we take the higher thermal expansion coefficient of the matrix into account. The matrix expands more rapidly than the carbides which are compressed. This pressure on an outer carbide border causes internal tensile stress which is perpendicular to the compression load, see **Fig. 8**.

This behaviour could explain the result from in plant trials stated in [3] where the work rolls from HiCr steel had higher service life than the work rolls made from HiCr iron.

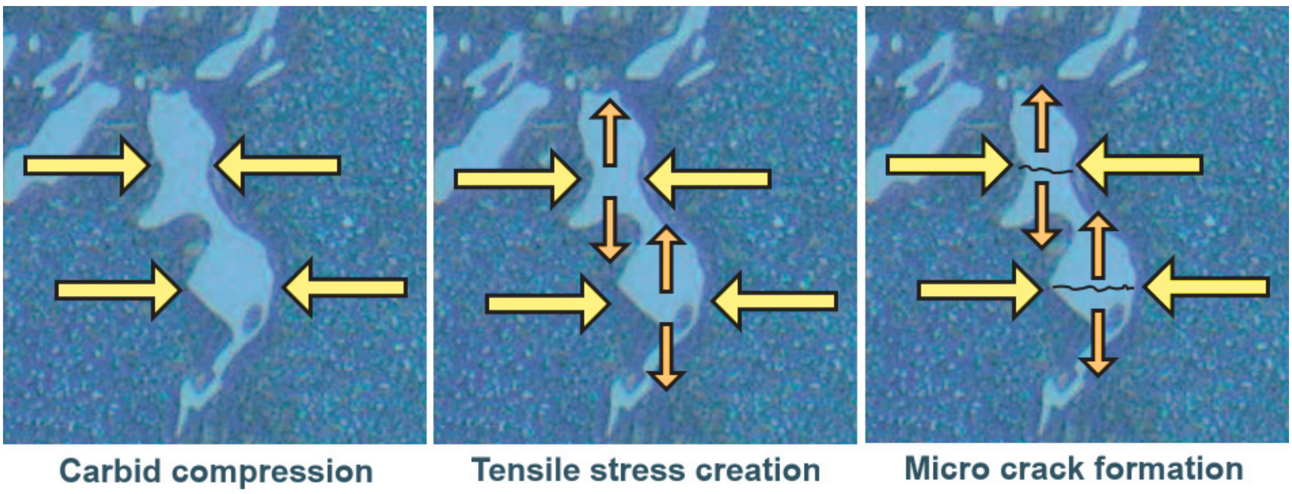

Fig. 8 The cause of micro crack formation inside of carbides. The long and thick carbides are compress by the surrounding matrix. The compression cause an elongation of carbides which creates the tensile stress creation. After the tensile stress reaches a certain level, the micro cracks appears

CONCLUSIONS

The microstructure simulation proved to be a solid tool for the improvement of a work roll's service life. The analysis of HiCr iron-like microstructure reveals the probable cause of the parallel-to-surface crack formation inside M_7C_3 carbides. The thermal fatigue was identified as the degradation mechanism responsible. The author suggests naming it secondary thermal fatigue to distinguish if from the well know primary fatigue, which leads to perpendicular-to-surface cracks network.

The secondary thermal fatigue mainly occurs inside long, thin carbides. Because of heat, the matrix and carbides are forced to expand. The expansion could freely progress only in a radial direction. The higher thermal expansion coefficient of the matrix creates compressive load on the outer carbide borders which forces the carbides to a radial prolongation. This prolongation causes tensile stress inside the carbides and it leads to tearing carbides apart.

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