LOADING AND TEMPERATURE DEPENDANT FATIGUE PARAMETERS OF WORKING ROLL SURFACE LAYER MATERIAL[1]

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Abstract

This paper deals with loading and temperature dependant fatigue parameters of working roll surface layer material. The research is performed on working rolls, where High Chromium Steel (HCrS) is used for roll's shell material. Before fatigue testing, monotonic mechanical properties (ultimate compressive and ultimate tensile strength) are determined at different temperatures, using standardized testing procedures. Fatigue testing is performed on a servo – hydraulic testing machine with consideration of different loading ratios (R = 0, R = -1) and different initial temperatures of the specimens (20 °C, 600 °C). On the basis of the experimental results the S – N curves are constructed, from which typical fatigue parameters (the fatigue strength coefficient σ_f' and the fatigue strength exponent b) are determined. After fatigue testing a comprehensive research of fracture surfaces is performed using the Scanning Electron Microscope (SEM). Thereafter, the line profile Energy Dispersive X–ray Spectroscopy (EDS) is performed to determine content elements and carbides inside crystal grains and around grain boundaries. Experimental results presented in this paper will serve as a basis for further research related to fatigue behaviour of working rolls in hot strip mills made of HCrS.

Keywords: Experiments; High cycle fatigue; High chromium steel.

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1 INTRODUCTION

High Chromium Steel (HCrS) is carbide based steel material which is usually used for hard and wear resistant working layer of double layered working rolls in hot strip mills. In these rolls the shell is centrifugally cast and made of HCrS; while for the core a normal gravity casting procedure as a combination of perlitic – feritic nodular graphite cast iron is used which assures the required toughness of core material. Working rolls made of HCrS normally operate at roughing stands and are usually mounted at the beginning of the rolling process, where slabs are reduced to thick plates.
The main goal of a rolling process is to achieve the required plastic deformation of the rolling plates. This is accomplished on a rolling mill where rotating rolls draw the plate or strip into the gap and force it through the exit, causing the required reduction of thickness.[(1,2)] To achieve this goal, working rolls must be designed in such a way that they provide demanded plastic deformation of rolled metal through the whole service life of the roll. Correct manufacturing process and heat treatment have a significant influence to reach the appropriate load capacity of rolls during complete service life of the rolling process. Podgornik, Milanović and Vižintin[(3)] 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 inappropriate production parameters, such as turning and grinding speed, high tensile residual stresses could be present on the roll's surface, which could lead to a brittle fracture of the roll already in its production phase. On the other hand, working rolls are during the rolling process thermo-mechanically loaded. Mechanical loads are presented on working rolls when plastic deformation of rolled metal occurs on two surfaces. Firstly in the area between working roll and rolled metal and secondly on the contact between working and back up roll. Thermal loadings on working rolls result in heat transfer between working roll and rolled strip. A small thermal stress field could also appear in the area between working and backup roll because of friction. Schröder[(4)] studied the heat transfer from rolled metal to the working roll and consequently the increasing temperature of surface layers of the working roll. Results of his investigation show that the temperature of working rolls vary from 100°C to 600°C during one revolution of working roll. The largest temperature is valid for the time when the working roll is just in contact with rolling strip, while the smallest one is valid for the roll cooling area.
When studying thermo-mechanical loading of rolls during one revolution, two types of stress and strain fields in the contact area can be considered: (i) stresses in the area between working and back up roll, where the elastic stress field in the contact area can be determined using Hertzian contact theory,[(5)] (ii) stresses in the area between working roll and rolled metal, which are widespread through the larger contact field. In both cases the multi-axial stress field should be considered, where the principal stresses are acting in radial and tangential (rolling) directions. In the radial direction the compressive pulsating load at loading ratio $R = 0$ is dominant, while in the tangential direction a completely reversed loading at loading ratio $R = -1$ could be detected. León et al.[(6)] namely showed that in the neutral zone of the contact area between working roll and rolling strip, the tangential stresses on working roll surface are changing from tension to compression.
To determine the fatigue behavior of working rolls different approaches can be used. Knez, Kramberger and Glodež[(7)] combines High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF) theory for determination of service life of structural elements made of

high strength steel S1100Q. In the presented study the HCF approach is considered because of expected high number of stress cycles during complete service life of working rolls. It is in agreement of the basic concept of HCF-approach, also known as “Stress life approach”, which is usually used as a dimensioning criterion of dynamically loaded engineering components and structures which operate in the median fatigue area of *S* - *N* curve (Figure 1[(8)]).
In the median fatigue area the *S* – *N* curve can be mathematically expressed as:

$$\sigma = \sigma_f' \cdot (2N)^b \quad (1)$$

where σ_f' is the fatigue strength coefficient and *b* is the fatigue strength exponent.
The Eq. (1) is generally valid for uniaxial state of stress. However, the multi-axial stress field appears in the contact zone between roll and rolling strip. Therefore, the appropriate equivalent stress approach should be considered when studying the fatigue behavior of working rolls. Sometimes, the mechanical and thermal loading of working rolls is changing because of different boundary conditions in the exploitation. In such cases, an appropriate cumulative damage theory (Palmgren-Miner rule for example) should be taken into account when determining the load capacity or expected service life of treated mechanical elements.

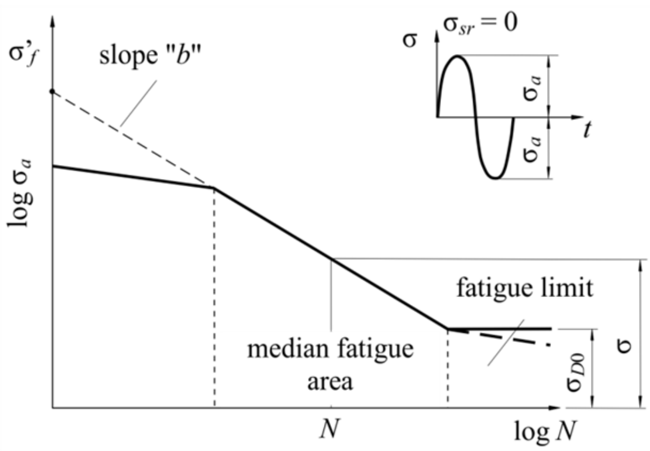

Figure 1. *S* – *N* curve at loading ratio *R* = -1.

The main purpose of this study is to determine the main material parameters of HCrS by monotonic and dynamic loading. In both cases, the material parameters should be determined by room temperature (20°C) and increased temperature (600°C). When analyzing the material parameters by dynamic loading, the typical fatigue parameters (the fatigue strength coefficient σ_f' and the fatigue strength exponent *b*) should be determined at different loading ratios: (i) *R* = −1 (completely reversed loading); (ii) *R*°=°0 (pulsating loading in compression). The important aim of this study is also the comprehensive metallographic investigation of fracture surfaces and the Line Profile Energy Dispersive X–ray Spectroscopy (EDS) which enables determination of elements and carbides content inside the crystal grains and around grain boundaries.

2 EXPERIMENTAL TESTING

The HCF fatigue properties (the fatigue strength coefficient σ_f' and the fatigue strength exponent *b*) have been determined at different temperatures and different loading ratios (*R* = 0 and *R* = −1) for treated material (High Chromium Steel - HCrS).

All specimens were cut out of the roll shell by using abrasive water blast technology. Therefore, it is assumed that specimens have similar characteristics as the roll. The complete manufacturing process of test specimens is shown in Figure 2.

Test specimens were cut out in such a way, that the axial loading of the specimen corresponds to the rolling direction in exploitation. Because of use of two different testing machines, two different shapes of fatigue testing specimens were prepared.

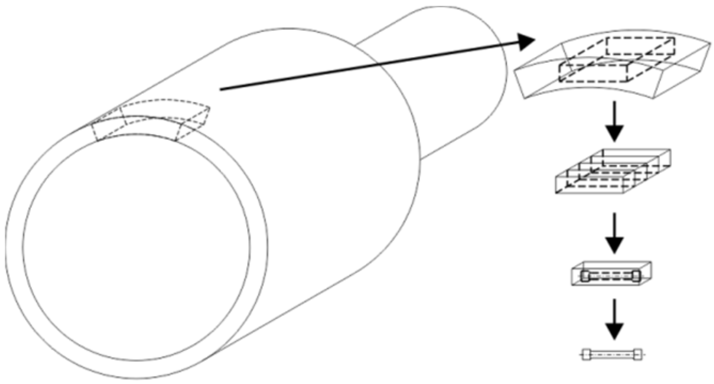

Figure 2. Manufacturing of test specimen.

Before experimental testing, a chemical composition of tested material was carried out by using an emission spectrometer Spectrolab (see Table 1). Figure 3 shows a microstructure of HCrS specimen etched with 2% Nital at various magnifications of 100x, 200x, 500x and 1000x by using the Olympus DP 12 camera in the Olympus BX 51 M light microscope, where eutectic M_7C_3 and secundary $M_{23}C_6$ chromium carbides can be observed. It is evident that the material matrix is composed with primary eutectic carbides M_7C_3 segregated along grain boundaries.

Table 1. Chemical composition of HCrS 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

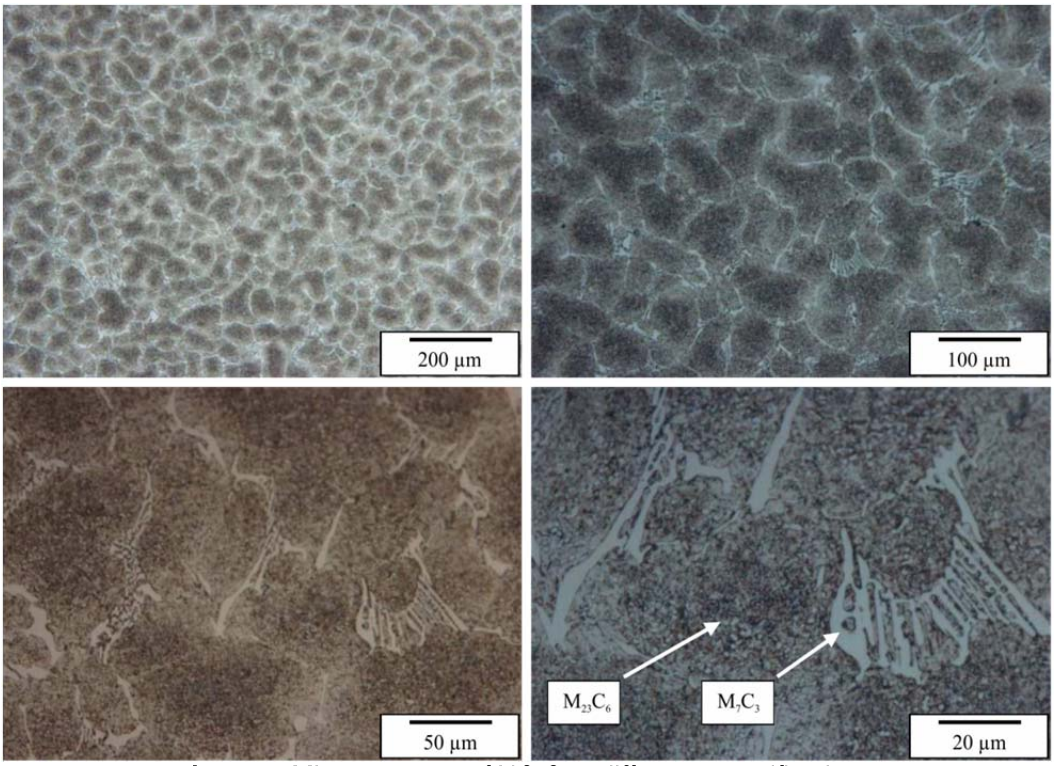

Figure 3. Microstructure of HCrS at different magnifications.

Figure 4 shows heat treatment of working rolls after manufacturing. Using such heat treatment the secondary carbides $M_{23}C_6$ participate in the matrix and in combination with other carbides contribute to the appropriate hardness, tensile/compression strength and wear resistance of treated material.

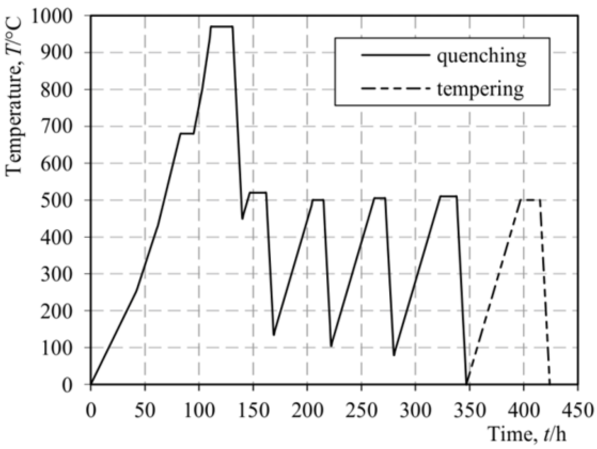

Figure 4. Heat treatment of working roll.

Figure 5 shows hardness distribution in the surface layer of working roll. It is evident that hardness is almost unchanged up to the border between working layer and core at depth approximately 80 mm under the surface. It can also be seen that the working layer with the average hardness 57 HRC is much harder if compared to the core where hardness is around 20 HRC.

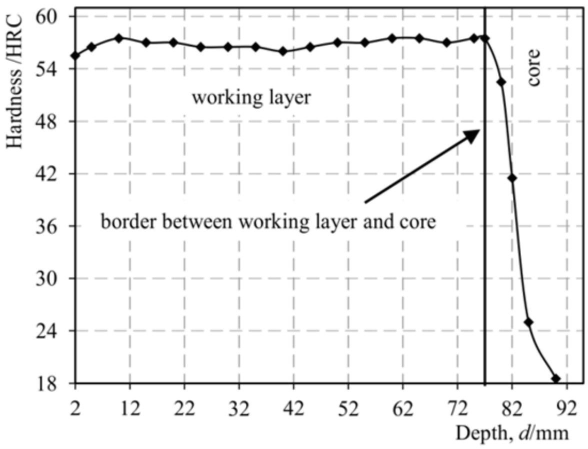

Figure 5. Hardness distribution in the surface layer of working roll.

Before fatigue testing, monotonic tensile[9] and compressive tests have been done at different temperature levels. First specimen was tested at room temperature; the second one at 100°C and for each subsequent test a temperature was increased for 100°C until final temperature 1000°C was reached. To determine monotonic mechanical properties of HCrS before and after heat treatment, a special monotonic tensile test at room temperature was performed, where specimens were cut out of a Y – cast ingot using water blast technology.[10]

Fatigue testing was performed on two different testing machines. Specimens loaded at room temperature have been tested on the servo – hydraulic fatigue testing machine Instron 1255 with computer aided control unit and an Instron 8500 data recording system. The MTS 810 fatigue testing machine has been used for the testing procedure at 600°C. The used increased temperature corresponds to the temperature which is reached by heat transfer between rolling strip and surface of working rolls.[4] To determine the *S* - *N* curve and consequently the fatigue parameters of HCrS, different load levels were prescribed for each test specimen. The first load level has been chosen with consideration of previously determined monotonic mechanical properties. Therefore, the first load level was set up a bit lower in comparison to the Ultimate Tensile Strength (UTS) and Ultimate Compression Strength (UCS). Thereafter, the load level was decreased for each subsequent test in order to increase the number of loading cycles up to the specimen failure.

As it is described in the introduction, the rolling process results in principal stresses acting in radial and tangential (rolling) directions at appropriate load ratios $R = 0$ and $R = -1$. This assumption has also been considered by the fatigue testing where the same load ratios have been performed. Here it should be pointed out that the load ratio $R = 0$ is not in agreement with the standard rotating bending test procedure,[11] where the specimen is subjected to fully reversed loading ($R = -1$). On the other hand, the experimental results, given at loading ratio $R = 0$ in compression enable us a direct determination of loading cycles until failure using eq. (1) without consideration of mean stress effect. However, the mean stress effect must be taken into account when data given from fully reversed loaded specimen ($R = -1$) are used when determining the service life or working rolls where the load ratio differs, which is evident from previous assumption.

After fatigue testing a complete fracture analysis has been done using the Scanning Electron Microscope JEOL JSM– 5610. An Energy Dispersive X – Ray Spectroscopy was used to determine the presence of elements in carbides in the treated material;

moreover a Line Profile EDS analysis was applied to investigate the change of concentration of different elements along the line which intersected one grain.

3 RESULTS

Figure 6 shows the diagram σ–ε for HCrS at room temperature for test specimens before and after heat treatment.

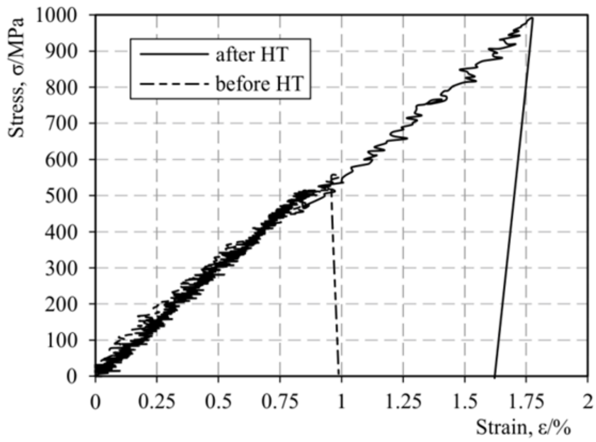

Figure 6. Diagram σ–ε for High Chromium Steel- HCrS at room temperature, before and after heat treatment.

Here, the raw test specimens were cut out of Y–cast ingot while heat treated specimens were cut out of roll shells. It is evident from Figure 6 that heat treatment, as described in Figure 4, significantly improves the monotonic strength properties (ultimate tensile strength is approximately 553 MPa for raw specimen and 990 MPa for heat treated specimen). The shape of σ–ε curve is approximately the same for both specimens and shows that there is no significant plastic deformation before breakage. Metallographic investigation has shown that the fracture surface is completely flat in both cases, which confirms the brittle fracture behavior of tested material.

Figure 7 shows ultimate tensile strength (UTS) and ultimate compression strength (UCS) at different temperatures of test specimens.

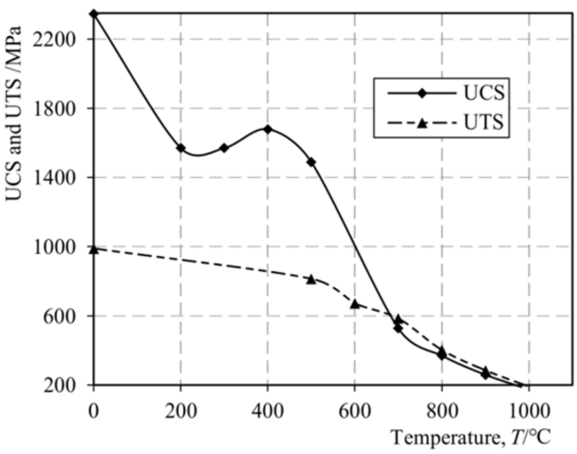

Figure 7. UTS and UCS as a function of testing temperature.

It can be seen that the main difference between UTS and UCS appears at room temperature, where UCS is almost 2.5 times higher than UTS. Both, UTS and UCS, are decreasing with increase of temperature until final tested temperature 1000°C. There is some anomaly at UCS between 250 and 400°C, where unexpected increase of strength can be observed.
The change of modulus of elasticity as a function of temperature is shown in Figure 8.

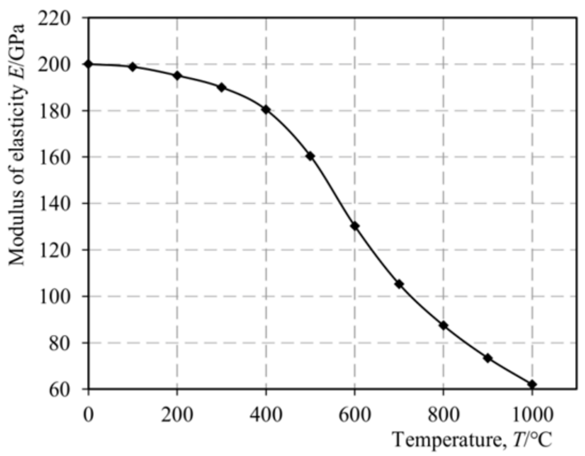

Figure 8. Modulus of elasticity as a function of testing temperature.

It is evident that the modulus of elasticity decreases as the temperature increases. The most rapid fall of Young's modulus can be observed between 500°C and 700°C.
Fig. 9 represents experimental results of fatigue tests under different testing temperatures (from 20°C and to 600°C) at loading ratio $R = -1$. The appropriate *S*°–°*N* curves are plotted in the range between 10^3 and 10^6 stress cycles which correspond to the typical median fatigue life.

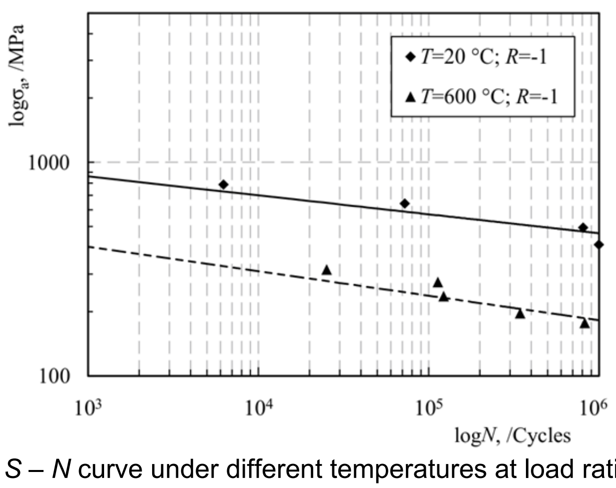

Figure 9. *S* – *N* curve under different temperatures at load ratio *R* = –1.

A similar procedure has also been done also at the loading ratio *R* = 0 in compression (see Figure 10).

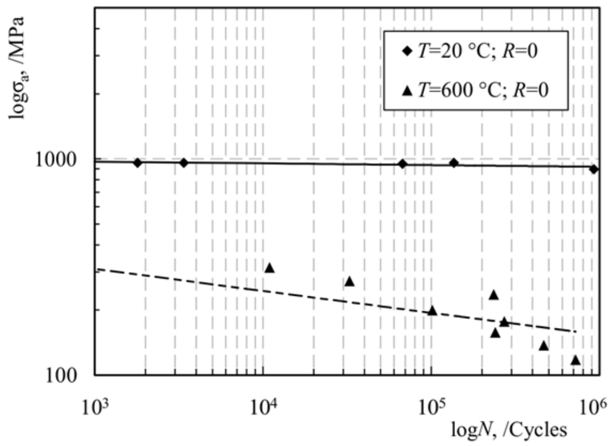

Figure 10. *S* – *N* curve under different temperatures at load ratio *R* = 0.

Experimental results presented in Figs. 9 and 10 have then been mathematically analyzed with the final goal to determine fatigue strength coefficient σ_f' and fatigue strength exponent *b* of HCrS under given boundary conditions(12) (see Table 2).

Table 2. High cycle fatigue coefficients of HCrS

Conditions	σ_f' [MPa]	*b*
T = 23 °C; *R* = –1	1481	–0,07347
T = 23 °C; *R* = 0	1032	–0,00801
T = 600 °C; *R* = –1	965	–0,11490
T = 600 °C; *R* = 0	667	–0,10123

When analyzing the *S* – *N* curve at *R* = 0 at room temperature it can be seen that the alternating stress has a relatively small influence on the reached fatigue life of tested specimens (very gentle slope of *S* – *N* curve in Figure 10). This is not the case at *R*°=°–1, where the small change of the alternating stress results in the significant change of the fatigue life. When changing the testing temperature to 600°C, the *S*°–°*N* curves at both load ratios (*R* = –1 and *R* = 0) are more comparable and almost parallel.
From experimental results in Figures 9 and 10 can be concluded, that the tested material shows extremely good fatigue resistance at room temperature (especially for load ratio *R* = 0), while for other loading conditions (*R* = –1, 600°C) the fatigue behavior is comparable to other high strength materials.
After fatigue testing a comprehensive metallographic investigation of fracture surfaces has been done using SEM. Figures 11a and 11b show small unbounded cracks in the area of eutectic carbides M_7C_3 which grow along grain boundaries (transcrystalline crack growth) until they reach chromium carbides where they are stopped or segregated.

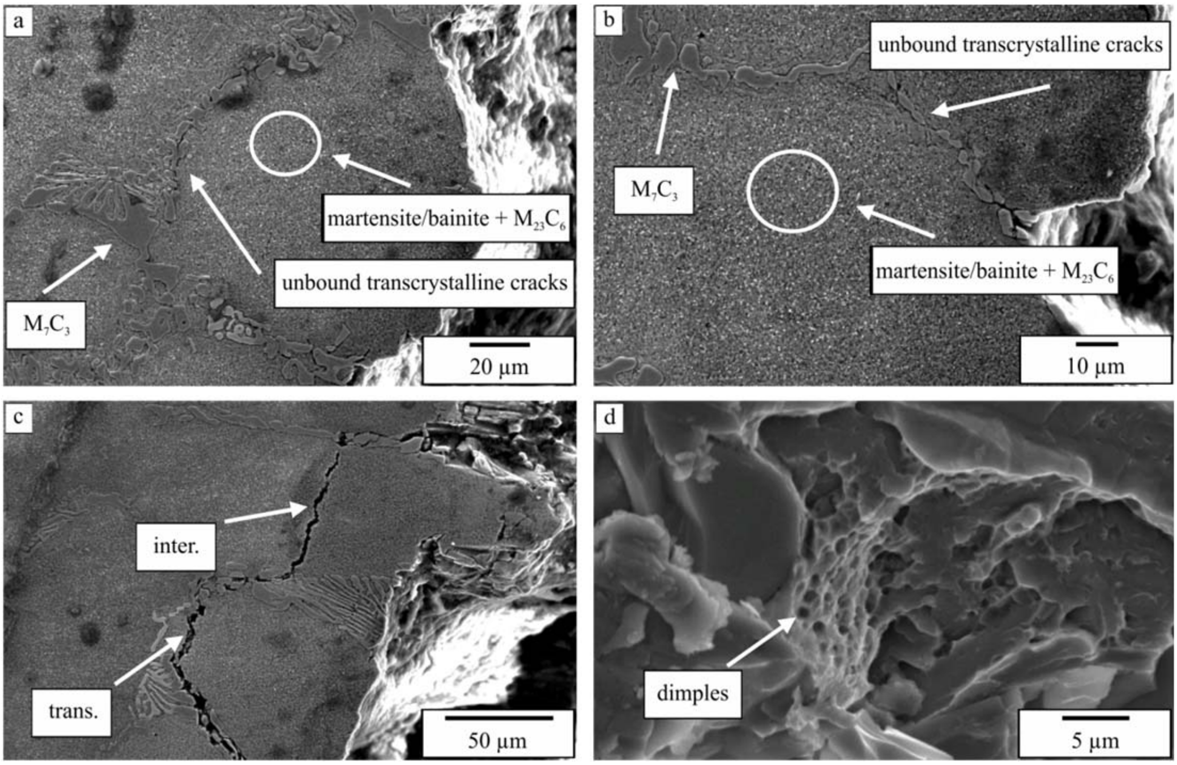

Figure 11. Fracture surfaces of tested specimens: a), b) unbounded transcrystalline cracks, c) intercrystalline crack, d) small dimples on the surface.

Sometimes, a crack may grow through crystal grains (intercrystalline crack growth) as shown on Figure 11c. An interesting fracture surface is shown in Figure 11d, where really small dimples can be observed which may represent a small level of ductile fracture. Mentioned phenomena practically does not have a role, when material brake, and could be neglected

Figures 12 and 13 show a Line Profile EDS Analysis made on the specimen tested at room temperature and at 600°C. Results of this analysis give us a possibility to determine the quantity change of each element through crystal grains. In both cases it was observed that chromium carbides are presented along the grain boundaries. It is evident from Figure 12 that with a decrease of chromium concentration ferrous begins to rise and visa versa. Beside chromium carbides, also molybdenum carbides are also important for mechanical properties of treated material, such as hardness, UTS, UCS, fatigue and wear resistance.

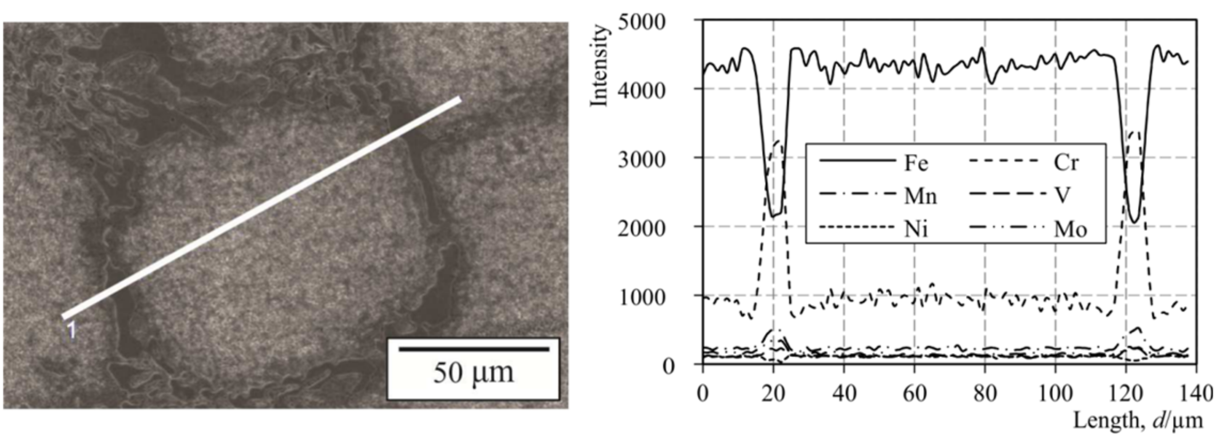

Figure 12. A Line Profile EDS Analysis on specimen tested at room temperature.

Similar statements have also been observed from a Line Profile EDS Analysis at temperature of 600°C (see Figure 13). The only difference could be observed in the shape of carbides near grain boundaries which look like a “saw blade”; this may be a result of high temperature fatigue where chromium particles dissolute into the grain more easily as at room temperature.

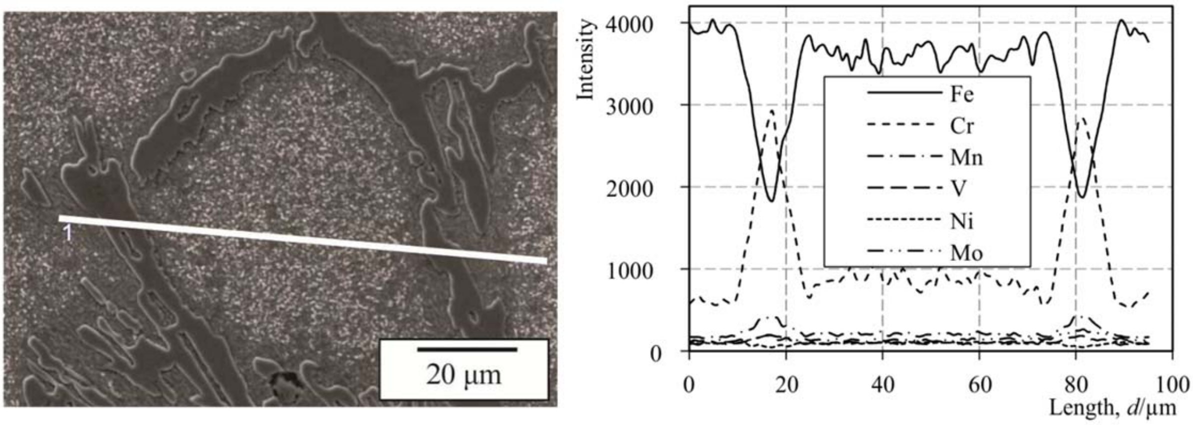

Figure 13. A Line Profile EDS Analysis on specimen tested at 600°C temperature.

The results of the metallographic investigation show that beside chromium carbides also molybdenum carbides are presented in the material microstructure, which could play an important role on mechanical properties of HCrS. An important conclusion of this study is also the dissolution of chrome from chromium carbides M_7C_3 to grains martensitic/ bainitic matrix, which can only happen at elevated temperature. This phenomenon is visible if we compare both of the curves for chrome presence near grain boundaries in Figures 12 and 13 (the curve for specimen tested at 600°C does not decrease so rapidly as in the case when the specimen is tested at room temperature).

4 CONCLUSIONS

Experimental investigation of monotonic and fatigue properties of HCrS usually used for hard and wear resistant surface layer of working rolls in hot strip mills is presented in this paper. Experimental results have shown that the appropriate heat treatment, where secondary chromium carbides participate inside martensitic/bainitic matrix, play a crucial role on mechanical properties of treated material.

On the basis of monotonic tensile and compressive tests it was established that the ultimate tensile strength (UTS) for the material with appropriate heat treatment is 400 MPa higher if compared to the raw material. When UTS and ultimate compression strength (UCS) were compared at room temperature, the UCS value was almost 2.5 times higher as UTS value. With the increase of testing temperature both UTS and UCS decreased and reached identical value at approximately 680°C. The strength behavior is by further increase of temperature practically the same for both, UTS and UCS.

According to experimental results from fatigue testing at different loading ratios and temperatures it can be concluded that HCrS has a very good resistance against fatigue especially at room temperature and loading ratio R = 0. With changing the temperature and loading ratio, a bit steeper slope of S – N curves could be observed. It is evident that the worst loading conditions appear at loading ratio R = −1 and temperature T = 600°C.

A comprehensive investigation of fractured surfaces has shown that a brittle fracture appears at practically all tested specimens. Only in some cases a relative small ductile dimples can be seen, especially for specimens tested at 600°C, but it was assumed that they have no significant influence on the fatigue properties of treated material.
A Line Profile EDS Analysis has also been performed, where results of elements' presence in the crystal grains and grain boundaries has been detected. This analysis has shown that the content of chromium carbides falls rapidly in the direction from the grain boundary to the center of crystal grain.
Experimental results presented in this paper will serve as a basis for further investigations where the main goal is to determine service life of working rolls operating in hot strip mills. A comprehensive numerical simulation of hot rolling process and the subsequent computational analysis to determine the stress field in the contact area and finally the expected service life will be performed by using material data determined in this study.

Acknowledgements

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