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EXPERIMENTAL DETERMINATION OF FATIGUE PARAMETERS OF HIGH CHROMIUM STEEL UNDER DIFFERENT LOADING AND TEMPERATURE CONDITIONS

Matej Drobne, Nenad Gubeljak, Srečko Glodež

Preliminary notes
Fatigue investigation of high chromium steel (HCS) at different loading ratios ($R = 0$, $R = -1$) and different temperatures (20 °C, 600 °C) is presented in this paper. Before fatigue testing, monotonic mechanical properties (ultimate compressive and ultimate tensile strength) are determined at different temperatures, using standardized testing procedures according to DIN 50125 standard. Moreover Charpy impact tests at different temperatures were done with specimens that comply with the standard ISO 14556. Fatigue testing is performed on a servo – hydraulic testing machine with consideration of different loading conditions as described above. 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 investigation of fracture surfaces is performed using the Scanning Electron Microscope (SEM). Experimental results presented in this paper will serve as a basis for further investigations related to fatigue behaviour of real working rolls in hot strip mills made of HCS.

Keywords: *experiments, high chromium steel, high cycle fatigue*

Eksperimentalno određivanje parametara zamornog ponašanja visokokromnog lijevanog čelika pri različitim režimima opterećivanja i temperature

Prethodno priopćenje
U članku je razmatrano zamorno ponašanje visokokromnog lijevanog čelika za dva omjera minimalnog i maksimalnog opterećenja ($R = 0$, $R = -1$) te na dvije temperature ispitivanja (+20 °C, +600 °C). Mehaničke karakteristike materijala na vlak i tlak su određene za obje temperature na standardnim epruvetama u skladu s DIN 50125 standardom. Isto tako Charpy ispitivanja udarne žilavosti na različitim temperaturama urađene su u skladu s ISO 14556 standardom. Zamorna ispitivanja izvedena su na servohidrauličkoj kidalici za oba omjera opterećenja. Na osnovu eksperimentalnih rezultata dobivene su S – N krivulje s tipičnim parametrima zamaranja (koeficijent σ_f' i eksponent zamorne čvrstoće b). Nakon zamornih ispitivanja na karateristike na tlak obavljen je pregled prijelomne površine pomoću elektronskog mikroskopa. Eksperimentalni rezultati predstavljeni u ovom radu su osnova za daljna istraživanja zamornog ponašanja valjaka iz HCS materijala za vruće valjanje čelika.

Ključne riječi: *eksperimenti, visokokromni lijevani čelik, visoko ciklično zamaranje*

1 Introduction

High Chromium Steel (HCS) 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 HCS; 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 HCS 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 strip or plate 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 et al. [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 temperatures of working rolls vary from 600 °C to 100 °C during one revolution of a 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. Unlike Schröder whose results were given directly from the operating working roll, Kiss [5] investigates the change of temperature on cast iron roller's surface during rolling process, with using a special testing machine. Half of rotating ring shaped specimen was exposed to high temperature, while other half was cooled down by using different coolant. His results showed the number of cycles until fire cracks appeared on cast iron rolls surface because of thermal fatigue. Kiss et al. [6] also investigate correlations between the hardness and main alloyed elements such as chromium, molybdenum and nickel on cast iron rolls. Their investigations could help engineers to determine the optimal value of alloyed elements to assure the hardness of cast iron rolls.

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 [7], (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. [8] 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 et al. [9] combine 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 with 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 (see Fig. 1, [10]).

In the median fatigue area the $S-N$ curve can be mathematically expressed as: where σ_f' is the fatigue strength coefficient and b is the fatigue strength exponent.

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

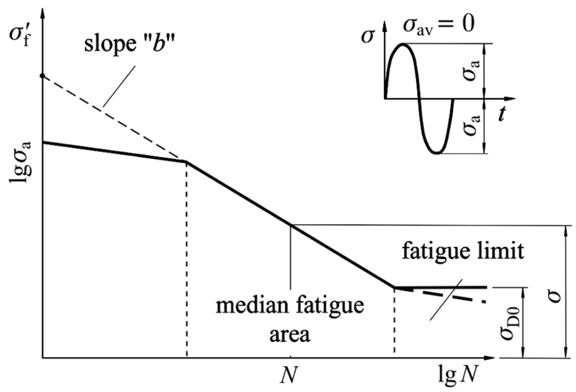

Figure 1 $S-N$ curve at loading ratio $R = -1$

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 behaviour 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 [10]) should be taken into account when determining the load capacity or expected service life of treated mechanical elements.

The main purpose of this study is to determine the main material parameters of HCS 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 analysing 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.

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-HCS). 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 manufacturing process of test specimens is shown in Fig. 2.

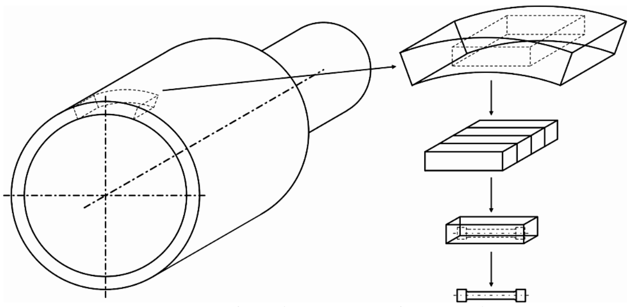
Figure 2 Manufacturing process of test specimens

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 specimens were prepared (see Fig. 3).

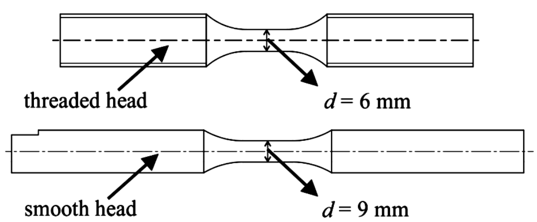

Figure 3 Two different types of test specimens

Table 1 Chemical composition of HCS determined with emission spectrometer

Element, wt. %										
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

Before experimental testing, chemical composition of tested material was carried out by using an emission spectrometer Spectrolab (see Tab. 1). Fig. 4 shows the microstructure of HCS specimen etched with 2 % Nital at various magnifications of 100×, 200×, 500× and 1000× by using the Olympus DP 12 camera in the Olympus BX 51 M light microscope, where eutectic M_7C_3 and secondary $M_{23}C_6$ chromium carbides can be observed. It is evident that the material matrix is composed of primary eutectic carbides M_7C_3 segregated along grain boundaries.

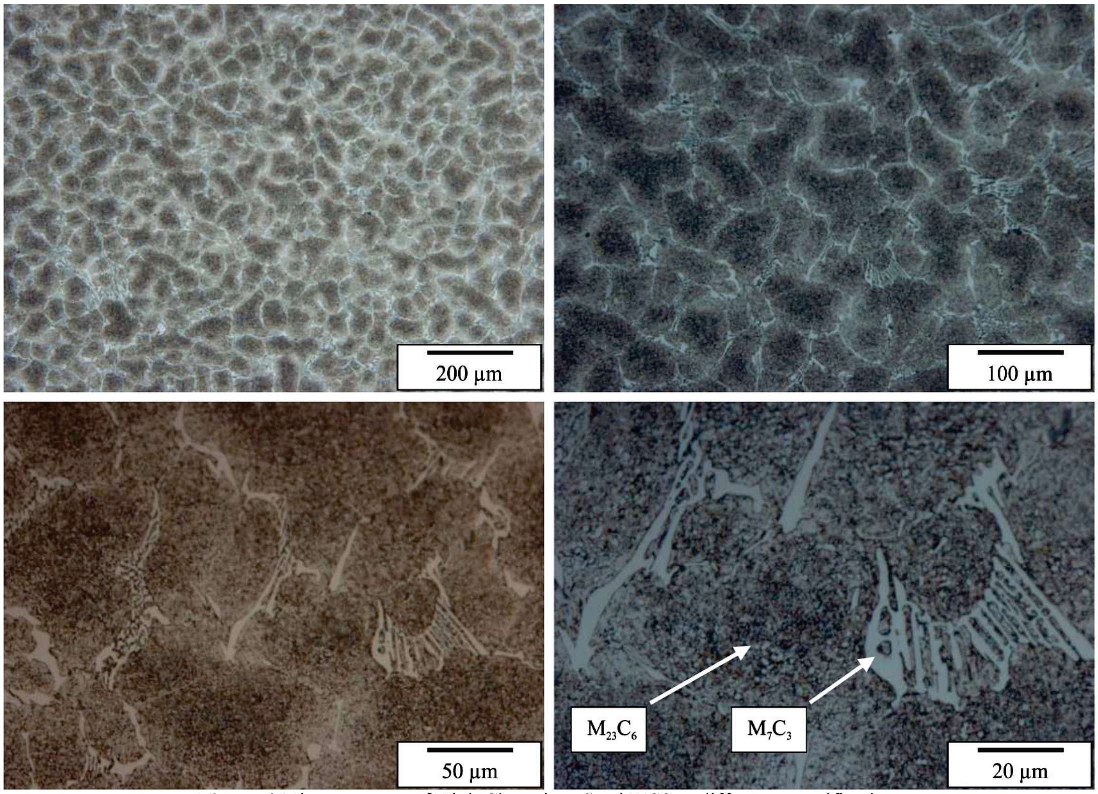

Figure 4 Microstructure of High Chromium Steel-HCS at different magnifications

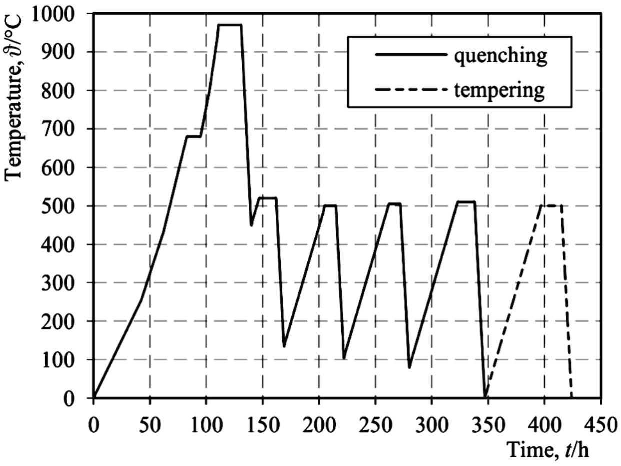

Figure 5 Heat treatment of working roll

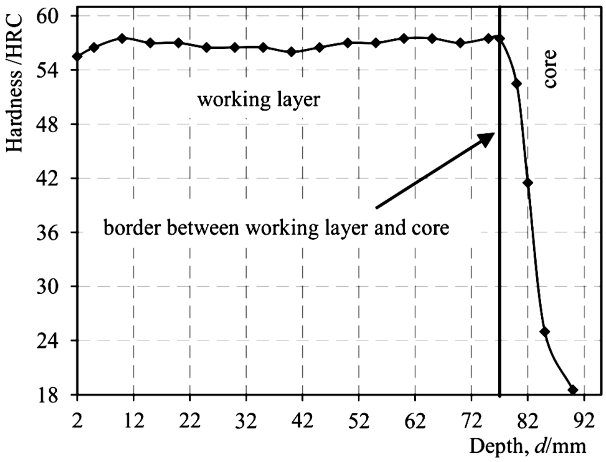

Figure 6 Hardness distribution in the surface layer of working roll

Fig. 5 shows heat treatment of working rolls after manufacturing. Using such treatment the secondary carbides $M_{23}C_6$ participate in the austenite matrix and in combination with other carbides contribute to the appropriate hardness, tensile/compression strength and wear resistance of treated material.

Fig. 6 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.

Before fatigue testing, monotonic tensile [11], compressive and Charpy impact tests [12] have been done at different temperature levels.

First specimen for monotonic tensile and compressive test was tested at room temperature; the second one at 100 °C and for each subsequent test the temperature was increased by 100 °C until final temperature 1000 °C was reached. To determine monotonic mechanical properties of HCS 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 (see Fig. 7 [13]).

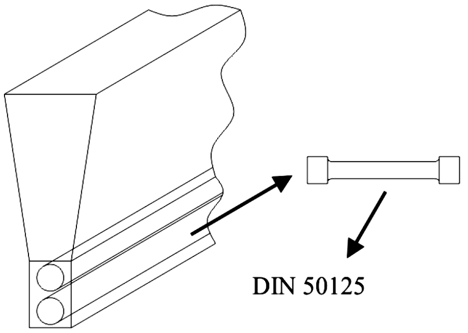

Figure 7 Monotonic test specimens manufactured from Y – cast ingot

Charpy impact tests with standard ISO V – notched specimen dimensions 10 × 10 × 55 were carried out by using the Amsler RKP-300 Charpy pendulum (see Fig. 8 [12]). Specimens were cut out from roll working layer in the same way as all other mentioned specimens, by using the abrasive water blast technology, while for notch a wire erosion process was used. Tests were done at temperatures 20, 300 and 600 °C. They were controlled by Vuhi-Charpy software [14], which enabled us to record the data of force and energy from the sensors during the impact.

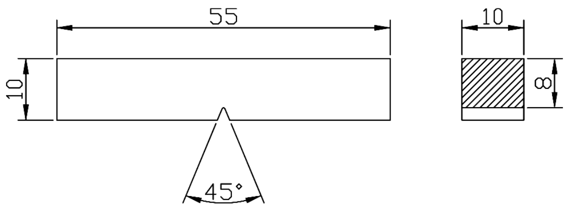

Figure 8 Standard ISO V – notched specimen

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 HCS, 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 with 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 [15], 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-SEM JEOL JSM - 5610.

3 Results

Fig. 9 shows the diagram σ–ε for HCS at room temperature for test specimens before and after heat treatment. Here, the raw test specimens were cut out of Y–cast ingot (see Fig. 7); while heat treated specimens were cut out of roll shells (see Fig. 2). It is evident from Fig. 9 that heat treatment, as described in Fig. 5, 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.

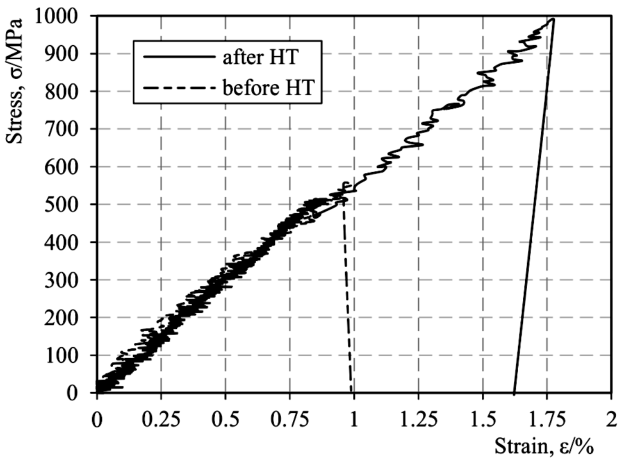

Figure 9 Diagram σ–ε for High Chromium Steel-HCS at room temperature, before and after heat treatment

Fig. 10 shows ultimate tensile strength (UTS) and ultimate compression strength (UCS) at different temperatures of test specimens. 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 Fig. 11. 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.

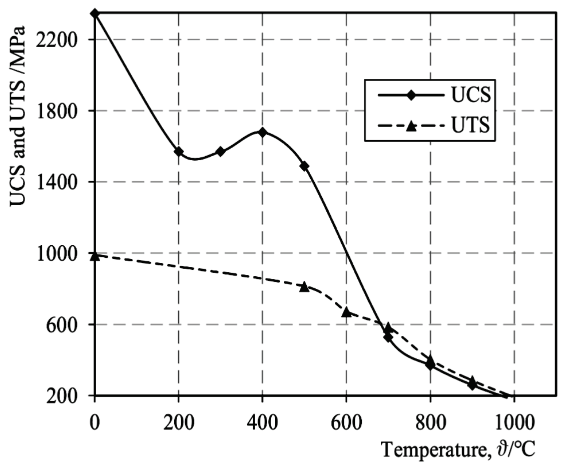

Figure 10 UTS and UCS as a function of testing temperature

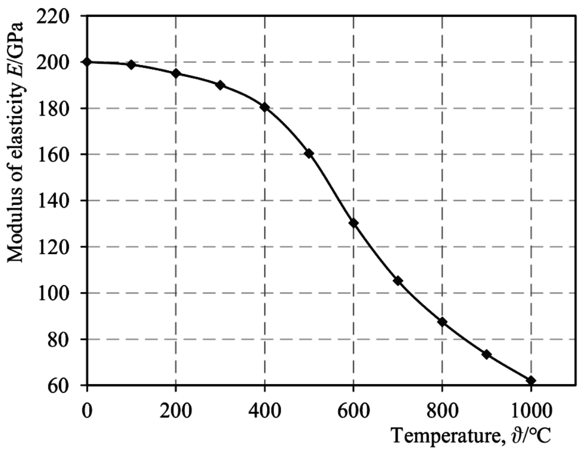

Figure 11 Modulus of elasticity as a function of testing temperature

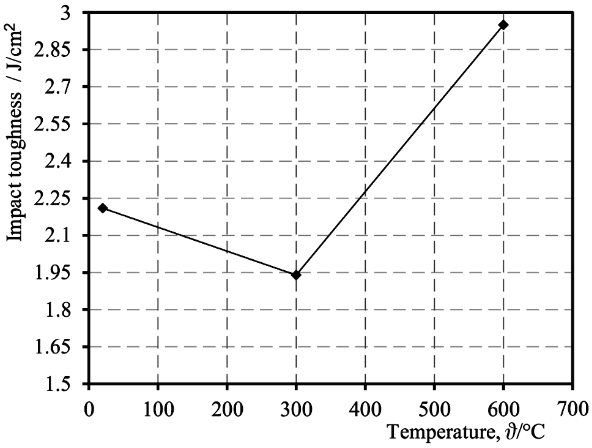

Figure 12 Charpy impact toughness as a function of temperature

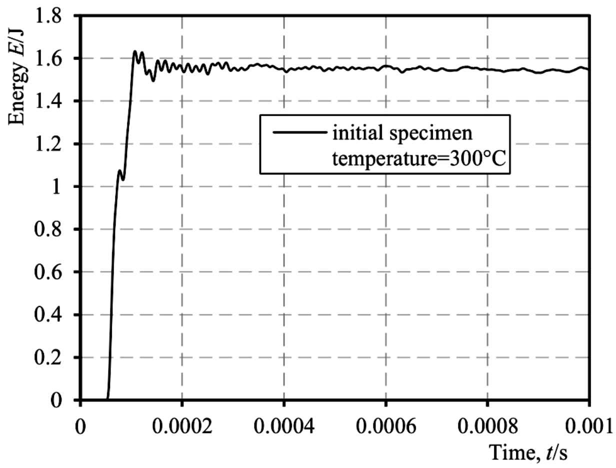

Figure 13 Energy for fracture during Charpy test as a time function

The impact toughness as a function of specimen initial temperature is presented in Fig. 12. It is visible that the initial temperature of the specimen has a little effect on impact toughness, which is very low. If we compare both of the boundary temperatures, rooms at 20 °C and 600 °C it is evident that the value of impact toughness is almost constant. At 600 °C the impact toughness is only by 0,74 J/cm^2 higher than the one measured at room temperature. Results show that temperature does not have a key role on fracture behavior of HCS. Fracture surface area is always completely flat.

Fig. 13 shows a correlation between energy for fracture during Charpy test as a time function. Due to brittle material characteristics (time needed for fracture is extremely fast – less than 0,1 ms) only one curve for test at 300 °C could be detected. It is evident that a little energy is needed for fracture.

Fracture surfaces of the specimens for Charpy impact test are imagined in Fig. 14. It is visible that with the rising of temperature of the specimen the significant difference in fracture area could not be observed.

If we compare Fig. 14a and Fig 14c it is visible that fracture surface in Fig. 14c is a little bit more toothed than one presented in Fig. 14a. This happens due to a little material softening at elevated temperature, but the nature of fracture is still brittle.

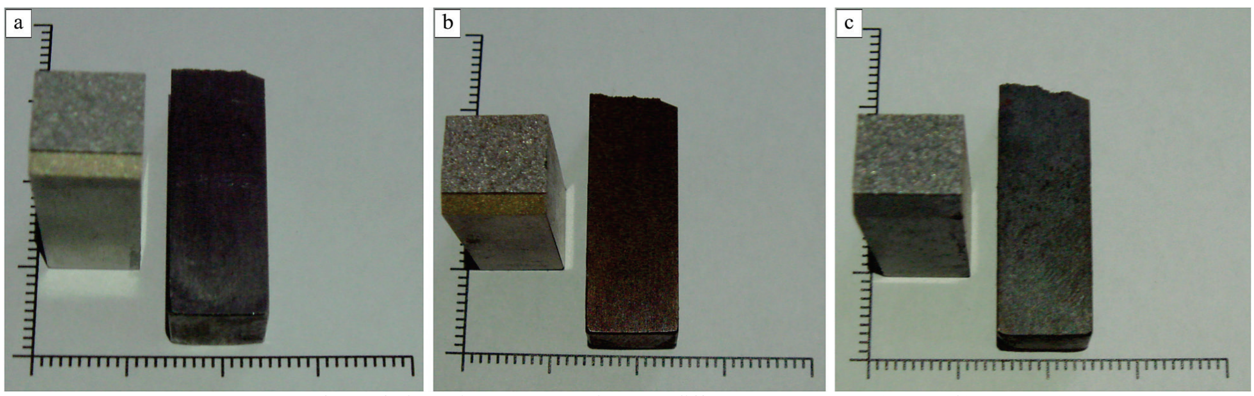

Figure 14 Fracture surfaces of Charpy impact test specimens at different temperatures; a) 20 °C, b) 300 °C, c) 600 °C

Fig. 15 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. A similar procedure has also been done at the loading ratio R = 0 in compression (see Fig. 16). Experimental results presented in Figs. 15 and 16 have then been mathematically analyzed [16] with the final goal to determine fatigue strength coefficient σ_f' and fatigue strength exponent b of HCS under given boundary conditions (see Tab. 2).

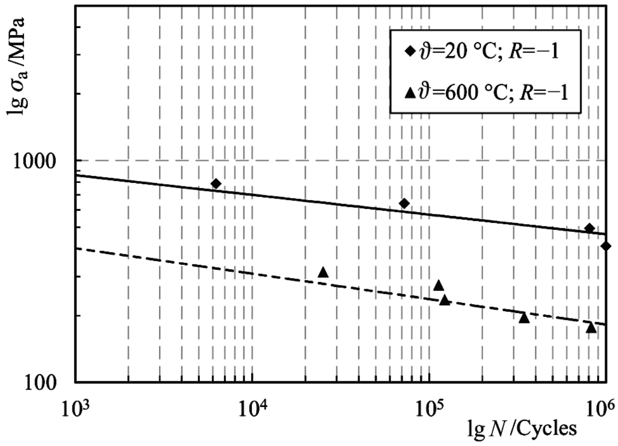

Figure 15 S – N curve under different temperatures at load ratio R = –1

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 Fig. 16). 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 Figs. 15 and 16 it 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 such as R = –1 at 600 °C) the fatigue behavior is comparable to other high strength materials.

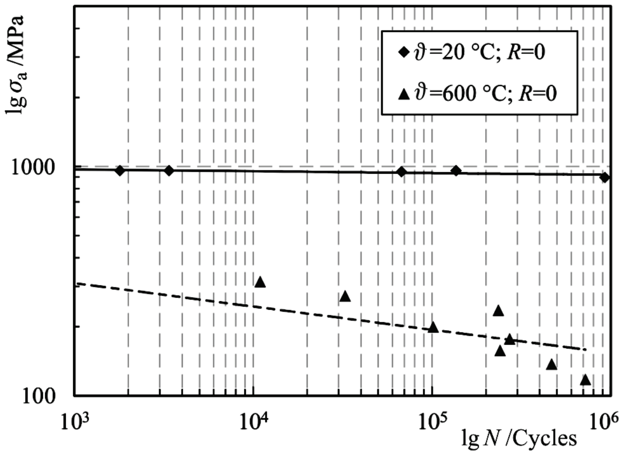

Figure 16 S – N curve under different temperatures at load ratio R = 0

Table 2 High cycle fatigue coefficients of HCS

Conditions	σ_f' / MPa	b
ϑ = 23 °C; R = –1	1481	–0,07347
ϑ = 23 °C; R = 0	1032	–0,00801
ϑ = 600 °C; R = –1	965	–0,11490
ϑ = 600 °C; R = 0	667	–0,10123

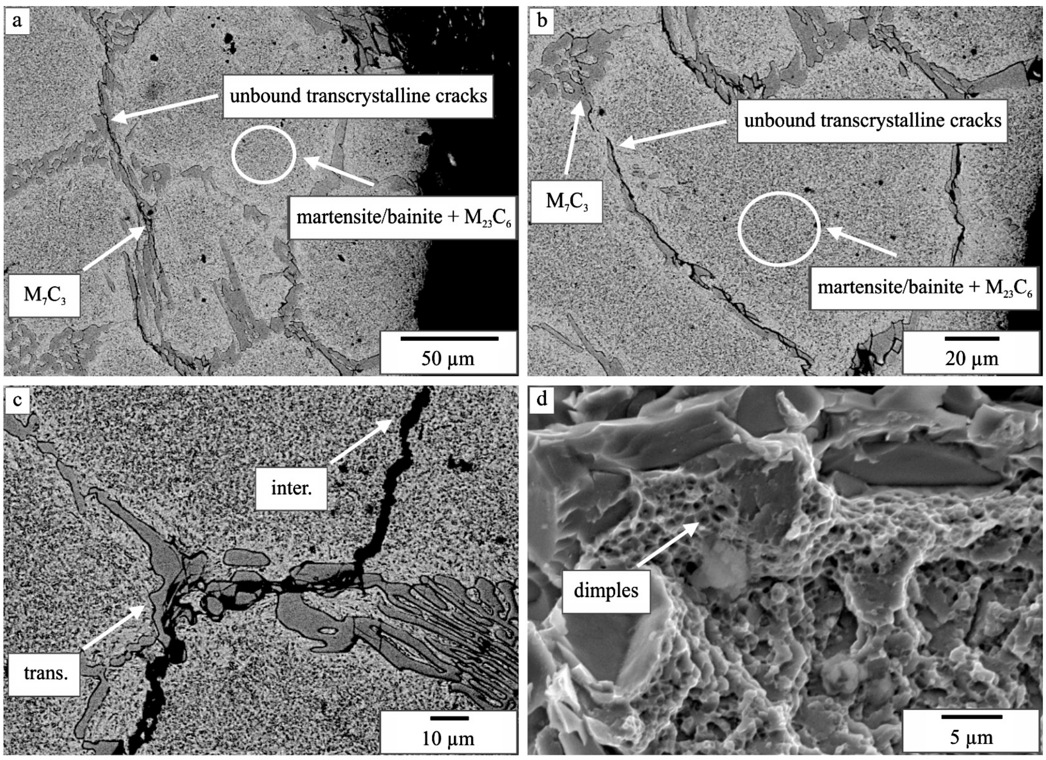

Figure 17 Fracture surfaces of tested specimens: a), b) unbounded transcrystalline cracks, c) intercrystalline crack, d) small dimples on the surface

After fatigue testing a comprehensive metallographic investigation of fracture surfaces has been done using SEM. Figs. 17a and 17b 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. Sometimes, a crack may grow through crystal grains (intercrystalline crack growth) as shown in Fig. 17c. Not only M_7C_3 carbides are presented in HCS microstructure, also secondary carbides $M_{23}C_6$ could be observed. Its locations are inside the grain in combination with austenite. An interesting fracture surface is shown in Fig. 17d, where really small dimples can be observed which may represent a small level of ductile fracture. Mentioned phenomenon practically does not have a role when material brakes, and could be neglected.

4 Conclusion

Experimental investigation of monotonic and fatigue properties of HCS 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 appear inside austenite 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 than 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.

Results of Charpy impact test at different temperature levels shows that temperature practically has no effect on impact toughness of HCS, it is very low and almost constant between 2 and 3 J/cm^2 According to the data recorded during testing, we can conclude that impact toughness increases at 600 °C by only 0,74 J/cm^2 from its original value at room temperature which is 2,21 J/cm^2. Fracture surface area is flat (brittle crack) for each temperature level.

According to experimental results of fatigue testing at different loading ratios and temperatures it can be concluded that HCS has a very good resistance to 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 relatively 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, what was proven also with Charpy impact test.

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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Authors' addresses

Matej Drobne
Valji d.o.o.
Železarska cesta 3
3220 Štore, Slovenia
E-mail: matej.drobne@valji.si

Nenad Gubeljak, prof. dr.
University of Maribor
Faculty of Mechanical Engineering
Smetanova 17, 2000 Maribor, Slovenia
E-mail: nenad.gubeljak@uni-mb.si

Srečko Glodež, prof. dr.
University of Maribor
Faculty of Mechanical Engineering
Smetanova 17, 2000 Maribor, Slovenia
E-mail: srecko.glodez@uni-mb.si