Termično utrujanje jeklenih valjev s povišano vsebnostjo kroma

MAGISTRSKO DELO

Gerard VALVERDE MONTRAVETA

Ljubljana, september 2014
Magistrsko delo je bilo izvedeno pod mentorstvom izr. prof. dr. Petra Fajfarja
Thermal fatigue of high chromium steel rolls

MASTER’S THESIS

Gerard VALVERDE MONTRAVETA

Ljubljana, September 2014
The master thesis was carried out under the mentorship of Assoc. Prof. Dr. Peter Fajfar
Table of contents

Acknowledgements .............................................................................................................. i

Izvleček ................................................................................................................................. ii

Abstract ................................................................................................................................ iii

Povzetek................................................................................................................................... iv

1. Introduction .......................................................................................................................... 1
   1.1 Problem definition, purpose and objectives of the thesis .............................................. 1
   1.2 Working hypothesis ........................................................................................................ 1
   1.3 Structure of the thesis ..................................................................................................... 2

2. Work rolls used in hot rolling mill ..................................................................................... 4
   2.1 Work rolls for hot rolling ............................................................................................... 4
   2.2 Temperature evaluation of work roll ............................................................................ 9
   2.3 Thermal fatigue of work roll ....................................................................................... 17
   2.4 Physical simulation of work roll thermal fatigue ......................................................... 20

3. Experiments ....................................................................................................................... 25
   3.1 Specimen ....................................................................................................................... 25
   3.2 Thermal fatigue testing ............................................................................................... 26
      3.2.1 Temperature distribution in the specimen cross section ...................................... 27
      3.2.2 Thermal fatigue testing ....................................................................................... 29
   3.3 Light and scanning electron microscopy ..................................................................... 32

4. Finite Elements Method Simulations ............................................................................... 34
   4.1 Material properties ....................................................................................................... 35
   4.2 Simulation parameters and conditions ......................................................................... 36
   4.3 Geometrical description ............................................................................................... 38
      4.3.1 First case ............................................................................................................... 39
      4.3.2 Second case ........................................................................................................... 39
      4.3.3 Third case ............................................................................................................. 40
5. Results and discussion

5.1 Crack initiation and propagation

5.2 Crack density and crack length

5.3 Temperature evaluation in the specimen

5.4 FEM simulation of work roll temperature

5.4.1 Influence of roll piece thickness and its initial temperature on work roll surface temperature

5.4.2 Influence of cooling conditions on work roll surface temperature

5.5 Temperature profile of work rolls

6. Conclusions

7. References
Acknowledgements

The fulfilment of this master thesis has been a great experience for me, not only for being able to work in a field of metallurgy that really interests me, but also because adapting to a new workplace and having made the project in another country and in another language represented a great challenge.

Firstly, I would like to express my gratitude to the Natural Science and Engineering Faculty and the University of Ljubljana, to the administrative staff.

Secondly, I would like to thank my mentor Assoc. Prof. Dr. Peter Fajfar the opportunity he has given me to do this project and the activities in which I had the chance to participate which supposed an unexpected large learning about metallurgy. I also want to express my gratitude to M.Sc. Celestin Nzobandora, Asist. Prof. Dr. Matjaž Knap, Asist. Prof. Dr. Aleš Nagode, Prof. Dr. Milan Terčelj and Tomaz Martinčič for their interest and sacrifice for helping me in this thesis.

Finally, I want to express my eternal gratitude to my parents, without them this experience would not have been possible. They have supported me to fulfil this project abroad and they have also covered most of the expenses here. I am also grateful to my brother for his constant support and to my partner for her help, support and patience. Because of this I want to dedicate this thesis to all of them.
Izvleček

V magistrskem delu je bil raziskan fenomen pojava razpok v vročem na površini delovnih valjev med nemotenim valjanjem in tudi v primeru, ko pride do ustavitve valjalnega stroja. Med vročim valjanjem so valji podvrženi izmeničnemu ogrevanju in ohlajanju. Njihova površina je izpostavljena hitrim temperaturnim spremembam zaradi stika z vročim valjanim materialom in zaradi ohlajanja valjev s hladno vodo. Izmenično ogrevanje in ohlajanje je povzročilo temperaturno utrujanje, ki je eden glavnih faktorjev, poleg mehanskega utrujanja in abrazije, ki vplivajo na hitrost propada površine.

Za določitev odpornosti na termično utrujanje valjev iz jekla z visoko vsebnostjo kroma sta bila izvedena dva različna testa. Prvi test omogoča simulacijo termično utrujanje delovnih valjev v primeru nemotenega valjanja. Nadalje pa drugi test omogoča raziskavo termičnega utrujanja delovnih valjev v primeru nepredvidenega zastoja valjanja. Oba testa sta bila izvedena na termo-mehanskem simulatorju metalurških stanj Gleeble 1500D. Temperaturno polje v delovnih valjih je bilo določeno z uporabo programske opreme NSC.SuperForm, ki temelji na metodi končnih elementov.

Dokazana je odvisnost temperature in vrste hladilnega medija na nastanek in rast razpok medtem, ko ta odvisnosti ni bila izrazita glede na dolžino kontaktnega časa. Raziskan je bil vpliv vhodne debeline in temperature valjanca na razvoj temperature na površini delovnega valja kot tudi v plasteh pod površino valja.

Magistrska naloga bo prispevala k boljšemu razumevanju nastanka razpok in njihovi rasti med nemotenim valjanjem in v primeru nenadne zaustavitve valjalnega stroja.
Abstract

Within the master work the phenomenon of appearance of firecracks on the surface of the work rolls that occur during hot rolling of flat products in the case of regular rolling conditions and in the case of the rolling mill stalls was investigated. During hot rolling work rolls are subjected to successive heating and cooling conditions. Their surface is exposed to rapid temperature changes due to the contact with hot rolled material and due to cold water used for rolls cooling. These cyclic heating/cooling conditions cause thermal fatigue which is one of the most important factors affecting the rate of surface deterioration as well as mechanical fatigue and abrasion.

Two different tests for the laboratory assessments of the thermal fatigue resistance of the high-chromium steel rolls were used. The first test enables a simulation of the work roll thermal fatigue in the case of regular rolling conditions. Furthermore, with the second test thermal fatigue of work rolls in the case of the rolling mill stalls was investigated. Both tests were implemented in a thermo-mechanical simulator of metallurgical states, the Gleeble 1500D. Finite elements method simulations were performed to determine the temperature distribution in the work rolls by using NSC.SuperForm software.

Evident dependence of the crack nucleation and their growth with the temperature and the cooling medium was found but no dependence due to the length of contact time was found. The influence of slab thickness and slab initial temperature to the temperature evolution in the surface layer of the work roll was estimated.

The master work contributes to better understanding of crack nucleation and their growth during the usual hot rolling conditions, as well as for the case of rolling mill stalls.
Povzetek


Poznanih je več fizikalnih simulacij za študij termičnega utrujanja delovnih valjev je. Li Chang Sheng L. et al. so razvili napravo za oceno termične obrabe valjev za vroče valjanje. Sestavljena je iz dveh okroglih plošč premera 1160 mm. Zgornja plošča je debeline 30 mm, spodnja pa 50 mm. Ogrevanje je indukcijsko in omogoča doseči temperature testiranja, ki so višje od 900 °C. Sestavni deli naprave so še rezervoar z vodo, vodna črpalka in visoko frekvenčni vir napajanja. Previdni material je iz bakra, medtem ko je bil preiskovani material hitrorezno jeklo. Kang C.G. in Kim Y.D. sta določila koeфициent toplotnega prenosa in naredila termično analizo pri valjanju tako eksperimentalno kot tudi z metodo končnih elementov. Za preiskovani material so uporabili jeklen valj (0,5 % C) zunanjega premera 170 mm in notranjega premera 130 mm ter širine 180 mm. Na valj so z uporabo 100 kN stiskalnice pritiskali ogrevano ploščo. S štirimi vgrajenimi termoelementi so merili temperaturno polje v valju. Anders Persson et al. so simulirali in vrednotili termično utrujanje orodnih jekel za delo v vročem. Preizkušanec iz je cevaste oblike dolžine 80 mm, zunanjega premera 10 mm in premera luknje 3 mm, ki služi za hlajenje. Za hlajenje so uporabili silikonska olja ali vodo. Ogrevanje je induktivno. Temperaturo na površini preizkušanca so merili s pirometrom. Garza-Montes-de-Oca NF in Rainforth WM sta raziskovala vpliv oksidacije površine valjev na trenje in s tem na obrabo valjev. Testna naprava je sestavljena iz dveh diskov premera 60 mm in debeline 16 mm. Zgornji disk pritiska na spodnjega, ki je preizkušanec, s silo 25 N. Preizkušanec je induktivno ogrevan. Na površino valjev se brizga zmes suhega zraka in vodne pare, ki ima temperaturo 85 °C. Temperatura je merjena z optičnim pirometrom.
Za fizikalno simulacijo termičnega utrujanja delovnih valjev smo uporabili simulator termo-mehanskih stanj Gleeble 1500D. Testna naprava je bila razvita na Katedri za preoblikovanje materialov na Naravoslovnotehniški fakulteti. Preizkušanci so bili odvzeti iz valjev z visoko vsebnostjo kroma. So valjaste oblike, dolžine 50 mm s premerom 10 mm na krajnjih delih in 8 mm na srednjem, zoženem delu. Ta oblika preizkušanca omogoča večji temperaturni gradient v srednjem delu, ki se ga uporabi za raziskave. V vzdolžni smeri preizkušanca je luknja premera 4 mm, skozi katero tečeta hladilna medija (zrak, voda). Temperatura se kontrolira s termoelementom, ki je točkovno navarjen na zunanji površini preizkušanca. Ogrevanje vzorcev je uporovno. Ohlajanje z vodo ali z zrakom, ter odstranjevanje vode iz notranjosti preizkušanca z zrakom je vodeno s parom magnetnih ventilov, ki sta računalniško krmiljena s termomehanskim simulatorjem Gleeble 1500D.


Izmerili smo tudi temperaturno polje v preizkušancu. Termoelemente smo točkovno privarili na zunanjih površini preiskušanca ter v globini 0,7 mm in 1,0 mm glede na zunanjih površin. Temperaturno polje ni homogeno. Najvišja temperatura je bila izmerjena na globini 0,7 mm. To si razlagamo kot posledico konduktivnega ogrevanja z izmeničnim tokom. Zaradi nastanka kožnega efekta je gostota električnega toka višja v površinskih plasteh, torej je posledično tudi višja temperatura. Temperatura površine pa je nižja zaradi odvajanja toplote v okolico s sevanjem in s konvekcijo.


Z metodo končnih elementov smo simulirali razvoj temperature v delovnih valjih pri nenadnem zastoju valjanja, torej za primer, ko je valjanec dalj časa v stiku z delovnimi valji. Uporabili smo programsko opremo NSC.SuperForm. V prvem primeru smo simulirali razvoj temperature na površini valjev pri različnih vhodnih debelinah valjanca in različnih vhodnih temperaturah valjanca. Vhodne debeline valjanca so bile 200 mm, 100 mm in 20 mm, vhodne temperature valjanca 900 °C, 1000 °C, 1100 °C in 1200 °C.
V drugem primeru smo prav tako raziskovali razvoj temperature na površini delovnih valjev v primeru odprave zastoja valjanja in hlajenja z vodo ali na zraku. Vhodni podatki za simulacijo so isti kot v primeru 1, le da po času 60 s simuliramo ohlajanje valjev. V tretjem primeru, pa smo se osredotočili na razvoj temperaturnega polja v delovnih valjih. Izbrali smo tri kombinacije vhodnih debelin in vhodnih temperatur valjanca z ozirom na dejanske pogoje izvajanja tehnologije vročega valjanja ploščatih izdelkov. Potrdili smo domnevo, da ima debelina valjanca pomemben vpliv na potek površinske temperature delovnih valjev.


Za določitev dolžine in gostote razpok smo uporabili optično mikroskopijo. Rezultate smo statistično obdelali z uporabo programske opreme STATISTICA.

V histogramih je jasno razvidno, da je večina vseh razpok (60%) v območju dolžin do cca 30 μm. Tretjina vseh razpok je v območju 20 μm. Večina kratkih razpok (~ 10 μm) je nastala pri ohlajanju z vodo. Količina dolgih razpok (l > 100 μm ) narašča z naraščajočo temperaturo. Pri temperaturi 500 °C znaša delež dolgih razpok 1 % in naraste na 13 % pri temperaturi 700 °C. Delež dolgih razpok je za 2 % večji pri ohlajanju z vodo. Tudi delež najdaljših razpok narašča z naraščajočo temperaturo. Opazen je rahel padec deleža najdaljših razpok z naraščajočim časom zadrževanja na temperaturi preizkušanja. Vpliv vrste hladilnega medija na nastanek najdaljših razpok ni bil zaznan. Gostota razpok narašča z naraščajočo temperaturo in naraščajočim časom zadrževanja na temperaturi zadrževanja.

V primeru simulacije nemotenega valjanja, torej pri termičnem utrujanju brez zadrževanja na temperature velja, je povprečna dolžina razpok narašča iz 30 μm pri 500 °C na 81 μm pri temperaturi 700°C. Gostota razpok je narastla od 6,21 razpok/mm pri temperaturi 500 °C do 7,62 razpok/mm pri 700 °C.

V primeru simulacije nenadne ustavitve valjalnega stroja so bile povprečne dolžine razpok pri času ogrevanja 15 s v splošnem daljše kot pri času ogrevanja 60 s. Nismo ugotovili vpliva vrste hladilnega medija na povprečno dolžino razpok. Gostota razpok je bila višja v primeru ohlajanja z vodo, kot pa v primeru ohlajanja na zraku.

Rezultati magistrske naloge prispevajo k boljšemu razumevanju mehanizmov nastanka in rasti razpok v delovnih valjih tako v normalnih pogojih valjanja, kot tudi v primeru ustavitve valjalnega stroja. In prav na tem segmentu je bistven prispevek magistrske
naloge, saj v nobenem objavljenem viru nismo zasledili obravnavo tega primera s fizikalno simulacijo. Ne nazadnje bodo nadaljnje raziskave vodile k izdelavi operativnih tehnoloških navodil za preprečevanje nastanka razpok v vročem pri normalni proizvodnji in pri zastoju valjanja ter s tem na podaljšanje življenjske dobe valjev.
1. Introduction

1.1 Problem definition, purpose and objectives of the thesis

Work rolls represent an important segment in the operating cost of modern rolling mill. They are expensive and a large number of work rolls must be in stock to assure the continuous operating of the mill. During hot rolling work rolls are subjected to successive heating and cooling conditions. Their surface is exposed to rapid temperature changes due to the contact with hot rolled material and due to cold water used for roll cooling. These cyclic heating/cooling conditions cause thermal fatigue which is one of the most important factors affecting the rate of surface deterioration as well as mechanical fatigue and abrasion. The surface of the working rolls is of essential meaning for the quality of hot rolled products. It influences the surface appearance as well as the transverse profile of the rolled product. The formation of cracks has a consequence of damaging the surface of the working rolls. These defects can also be imprinted in the rolling product. The mentioned defects are most pronounced on the stainless thick plates and are more visible after the leaching.

Within the master work the phenomenon of appearance of firecracks on the surface of the work rolls that occur during hot rolling of flat products in the case of regular rolling conditions and in the case of the rolling mill stalls was investigated. The stall band firecracks form a regular cellular pattern with spacing or cell size which is significantly larger and deeper than the normal fire crazing.

Rolls are double-layer centrifugal cast compound rolls with the cast iron outer layer with high chromium content and the core made either of a grey or a nodular cast iron. Work surface contains very hard chromium carbides, fine grained and equally distributed within the matrix which is made mainly from perlite as well as tempered martensite. High chromium rolls are primarily used in a rougher rolling mill for hot rolling of flat products.

The master work contributes to better understanding of crack nucleation and their growth during the usual hot rolling conditions, as well as for the case of rolling mill stalls.

1.2 Working hypothesis

During hot rolling work rolls are subjected to successive heating and cooling cycles. Their surface is exposed to rapid temperature changes due to the contact with hot rolled material and due to cooling with water sprays. These cyclic heating/cooling conditions cause thermal fatigue which is one of the most important factors affecting the rate of surface deterioration as well as mechanical fatigue and abrasion. If cooling is not intensive enough, wear of rolls and cracks appear. Cracks can appear after only a few turns of rolls, starting on the surface and growing perpendicular to the surface of the rolls. Crack density and crack length mostly depend on temperature gradient while alternating heating and cooling and the time (number of cycles) of thermal fatigue.
During a mill stall or a sudden stop of the rolling mill, the hot rolled strip is in contact with the work roll surface for an extended period of time. Due to extended (lasting up to several minutes) holding of rolls at high temperatures (850 °C – 1250 °C), the local overheating of work rolls appears. During that, the overheated surface expands in radial direction and contracts in axial and tangential direction. When the remaining stresses exceed the yield strength of the material, the stall band firecracks appear with netlike shape. The main task after this type of incident is to minimize the severity of the cracking that will result. There are several procedures at our disposal:
- to remove the rolls from the rolling mill;
- to rotate the rolls for about half an hour without water cooling or
- to cool down rolls with the water cooling system.

Two different tests for the laboratory assessments of the thermal fatigue resistance of work rolls were used. The first test enables a simulation of the work roll thermal fatigue in the case of regular rolling conditions. Furthermore, with the second test thermal fatigue of work rolls in the case of the rolling mill stalls was investigated. Both tests were implemented in a thermo-mechanical simulator of metallurgical states, the Gleeble 1500D. The real thermal fatigue cycling and stalling of the work roll were simulated by computer-controlled resistance heating and water cooling of the samples as well as air blowing was realized. The physical simulations of the roll thermal fatigue may give selective results of the influence of the testing parameters to the initiation and growth of the cracks.

1.3 Structure of the thesis

This thesis has been structured in seven different chapters: Introduction, Work rolls used in hot rolling mill, Experiments, Finite Elements Method Simulations, Results and discussion, Conclusions and References.

In chapter 2 background information can be found. Such information has been taken from published articles and handbooks. The aim of including this information is to get enough knowledge about thermal fatigue, rolling mills and rolls to be able to understand this work, why it is important and to get the possibility of reading it from a judgemental point of view. Work rolls for hot rolling, temperature evaluation of rolls, thermal fatigue of rolls and physical simulations of rolls thermal fatigue are the explained topics in chapter 2.

In chapter 3 performed experiments are presented. Used specimen, the way that thermal fatigue is tested and used microscopy is shown in this chapter. All data like technology, test methods, test thermal profiles, cooling ways, timing and experimental assembly is carefully detailed.

Chapter 4 includes rolling simulations with the use of finite element method. They try to reproduce the real rolling case in a factory as reliable as possible. Material properties, simulations parameters and conditions and description of each simulated situation are explained in this chapter.
Chapter 5 presents obtained results by performing experiments and simulations shown in chapter 3 and chapter 4. Discussion about obtained data is also included in this chapter.

Finally, in chapter 6, conclusions, reviews about performed work and possible future work suggestions are presented.
2. Work rolls used in hot rolling mill

2.1 Work rolls for hot rolling

Work rolls represent an important segment in the operating cost of modern rolling mill. They are expensive and a large number of work rolls must be in stock to assure the continuous operating of the mill. Although different kinds of mills are able to perform hot rolling operation, the ones with the highest productivities are the so-called semi-continuous and continuous mills. A continuous mill has different four-high stands, typically 4–5 roughing stands followed by 6–7 finishing stands. [1]

Rolls must be able to carry out extreme actions: very high thermal stresses and wear. These actions lead to the development of cracks, which means that sufficiently high fracture toughness is also an important requirement. In order to deal with all these actions, rolling rolls used in the roughening stands must possess very high resistance to thermal fatigue and oxidation along with high fracture toughness (the same properties are also required for initial finishing stand rolls). [1]

Historical development of materials used in rolling mills

In the 19th century basically unalloyed grey iron - modified only by various carbon equivalents and different cooling rates (grey iron chill moulds, or sand moulds) - and forged steel was used for rolls. The cast iron grades varied from mild - hard to half - hard, to clear chill, where the barrel showed a white iron layer (free of graphite) and grey iron core and necks due to reduced cooling rate. This type of rolls were used for flat rolling without any roll cooling in sheet mills, as long sheet - mills existed (end of 20th century). Later on cast steel rolls were developed with a carbon content up to 2,4 %, with and without graphite, and are still produced today.

Around 1930 Indefinite Chill Double Poured (ICDP) rolls were invented for hot rolling, especially for work rolls in finishing mills of hot strip mills, which were also used for many other applications such as roughing stands of hot strip mills and work rolls in plate mills. This grade was to become the world standard for many years with very limited variations. Until today no other material could replace this grade for some applications. In the late 1990s finally ICDP enhanced with carbide improved roll performance and started a new phase for this old grade, still successfully in use today in work rolls for early finishing stands of finishing hot strip mills (replacing high chromium iron and HSS - see further down) and for plate mills.

The use of high chromium iron (2 – 3 % C, 15 – 20 % Cr) and later on high chromium steel (1 – 2 % C, 10 – 15 % Cr) brought new materials, with high wear resistance and forgiveness into rolls. But this was only one major step towards greater productivity of rolls.
In 1985 by starting High-Speed-Tool Steel (HSS) materials were introduced into rolls and evolved the so-called Semi-Tool-Steel grades. After initial problems all changes brought new opportunities for better roll performance. After the introduction of new grades to the mills it was often necessary to change or improve rolling conditions. However, after some time rolls also improved and there were no further problems with new grades, only a better performance.

These entire roll grades are used for flat and long products. Additionally tiny rolls to produce wire rod use new, even more high-tech grades: sintered carbide is state-of-the-art, and ceramic rolls are also in trial use. However, for manufacturing these types of rolls there are still limitations in terms of size; equipment for bigger parts is not yet available.

Forged steel rolls were also improved for cold rolling to give higher hardness penetration after heat treatment by increasing the content of alloying elements. Basically the chromium content was increased from 2 % to 5 % and changed to (mainly) induction hardening. Chromium plating of work rolls after grinding and shot blasting increased the life of the necessary surface roughness.

In reality rolls are tools for metal forming, therefore the development of suitable roll materials goes hand in hand with the development of other cutting and non-cutting tools in metal industries. Rolls are relatively large tools with an extended life but ultimately they are only tools.

A summary of materials in use for the production of rolls is presented in table 2.1.
Table 2-1: Material used for rolling mill rolls. [2]

| Material | In Use Since | C [%] | Cu [%] | Mn [%] | Ni [%] | Cr [%] | Mo [%] | Materials | Carbide content [%] | Barren hardness (HV) | Forged (Fe or Cast)(C) | Ductile Casting (C) | Material otros | Compound Casting (C) | Max diameter | Work Rolls for Hot Rolling Strip and Plate | Work Rolls for Hot Rolling Long Products | Recent New Materials | Work Rolls for Hot Rolling Strip and Plate |
|----------|--------------|-------|--------|--------|--------|--------|--------|-----------|----------------|--------------------|-------------------|-------------------|-----------------|----------------|-----------------|--------------|----------------------------------------|----------------------------------------|-----------------|------------------------------------------|
| Ceramic  | 1900         |       |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Sintered Carbide | 1970       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| (Mild Hard / Half Hard – old grades of grey iron) | 1960       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Nodular Cast Iron | 1980       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| High Chrome Iron | 1985       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Carbide Enhanced ICIP | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| ICIP        | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| GHM("Cast Carbide") | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| CC (Chloral Chilled) | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Graphitic cast steel | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| High Chrome Steed | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| HSS (high speed steel) | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Adamite (hyper-eutectic steel) | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Serra - HSS | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Hypo-eutectic Steel | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |
| Material  | 1990       | 1 - 3 |        |        |        |        |        | Salts     |                |                   |                   |                   |                 |                 | 8 - 15       |                                      |                                         |                 |                                          |

Notes: Numeral in column 4 - 7 indicates park diameter is possible, and 8 - 15 indicates not possible.
Materials used in each stand

According to Belzunce et al., in general terms, the last hot strip mill (HSM) finishing stands use indefinite chill iron or modified indefinite chill iron rolls. High chromium iron or nowadays high speed steels (HSS) rolls are used in the initial HSM finishing stands. High chromium steel is the product usually used at the roughening stands (Figure 2-1). Table 2-2 shows the chemical compositions and final hardness (after heat treatment) of all these products.

Table 2-2: Chemical composition (wt %) and final hardness of HSM rolling rolls. [1]

<table>
<thead>
<tr>
<th>Material Type</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Nb+V</th>
<th>HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indefinite chill iron</td>
<td>3-3.5</td>
<td>1-2</td>
<td>3-5</td>
<td>0.2-0.5</td>
<td>-</td>
<td>56-60</td>
</tr>
<tr>
<td>Modified indefinite chill iron</td>
<td>3-3.5</td>
<td>1-2</td>
<td>3.5-6</td>
<td>0.2-0.5</td>
<td>0.5-1.5</td>
<td>57-61</td>
</tr>
<tr>
<td>HiCr Iron</td>
<td>2.3-3</td>
<td>13-18</td>
<td>0.4-1.2</td>
<td>1-3</td>
<td>-</td>
<td>53-59</td>
</tr>
<tr>
<td>HiCr Steel</td>
<td>0.8-2</td>
<td>10-14</td>
<td>1-2</td>
<td>3-5.5</td>
<td>0.3-1</td>
<td>48-56</td>
</tr>
<tr>
<td>HSS</td>
<td>1-2</td>
<td>3-8</td>
<td>1-7</td>
<td>5-10</td>
<td>2-6</td>
<td>58-62</td>
</tr>
</tbody>
</table>

Belzunce et al. also conclude that high speed rolls, which are high alloy products with a relatively low carbon content to produce very hard and well dispersed carbides, have the highest combination of hardness and toughness of all the products usually used in these applications, along with very high wear and thermal fatigue resistances, thus giving rise to the highest productivities and performance in the initial finishing HSM stands. In contrast, modified indefinite chill iron grades, with a high hardness, high wear resistance and low friction coefficient (due to the presence of graphite in their microstructures), are the best choice for the last finishing HSM stands. [1]

Ziehenberger and Windhager from Eisenwerk Sulzau-Werfen [3] Company schematize the conventional hot strip mill as in Fig 2-1, including materials used in each mill. They also describe the development of shell materials over the last years in Fig. 2-2.

Fig. 2-1: Work roll types for hot rolling of flat products. [3]
K. H. Schröder also discuss about different work roll grades for hot rolling used in each stands [4]. His explanations become useful in order to understand the reason why each material grade is used. Material grades for hot rolling are shown in following lists:

- Work rolls in roughing stands:
  - Nodular Iron: Still today in two high mills and low price in four high when too many rolls fail due to rolling accident
  - Adamite: Almost out of fashion, low price – low performance
  - High Chrome Iron: Good in some two stands
  - High Chrome Steel: State of the art
  - Semi-Tool-Steel: Successful in some applications – but not good for stainless

- Work rolls in early finishing stands of HSM (F1-3,4)
  - High Chrome Iron: State of the art
  - High Chrome Steel: Better than high Chrome Iron in some F1 stands (better forgiving)
  - ICDP: Only for stainless steels (ferritic) steels
  - VIS: Better than ICDP, hopefully comparable to High Chrome Iron
  - HSS: Successful in Japan, on trial elsewhere

- Work rolls in the last finishing stands of HSM (F7-5,4)
  - ICDP: The only grade in F7 outside Japan
  - VIS: Better performing than ICDP

- Summary
  - ICDP: The old fashion grade, with some advantages – might be replaced by VIS in the near future
  - High Chrome Iron: State of the art (specifically for high strength pipe steel)
  - High Chrome Steel: State of the art, very forgiving
High Chromium Steels for roughing work rolls comparison.

In order to get better knowledge about the new trends in hot strip mill roughing mills, Lecomte-Beckers et al. [5] compared the most widely used alloy for such an application, the High Chromium Steel grade (HCS), with semi-High-speed Steel (semi-HSS) which is the new grade developed to improve the overall performance of the work roll in the roughing stands of the HSM. The semi-HSS grade was studied starting from three chemical compositions closed one to another. The variation in the alloying elements was intended to assess, on one hand the effect of a small increase of the carbon content, and on the other hand the influence of the addition of a strong MC carbide forming element. Phase transformations temperatures, crystallization behaviour, interval of solidification and nature and composition of phases were determined.

In their study, comparison of different semi-HSS grades with Chromium steel done on roughing stands showed that the semi-HSS grade exhibits better general behaviour during rolling process. In table 2-3, a result of their comparison of roll behaviour for different work roll grades in roughing stands is showed.

**Table 2-3**: Comparison of roll behaviour for different work roll grades in roughing stands. [5]

<table>
<thead>
<tr>
<th>Roll grade</th>
<th>Bite</th>
<th>Wear resistance</th>
<th>Fire crack resistance</th>
<th>Surface quality</th>
<th>Campaign time</th>
<th>Safety in service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrome Steel</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Semi-HSS</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>HSS for roughers</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

↑ Excellent  ➔ Good  ➔ Satisfactory  ➔ Sufficient  ➔ Poor

2.2 Temperature evaluation of work roll

Evolution of the temperature or heat transfer in hot rolling has been analysed by many authors. It seems essential to get the best knowledge about the temperature behaviour in hot rolling mills rolls and the heat transfer in order to achieve the most effective and useful simulation of this process and to extract its most outstanding information for this thesis’ thermal fatigue evaluation interests.
Fig. 2-3: Comparison between calculated temperatures and experimental temperatures. Angular position of the roll versus heat flux, surface temperature and 0.2 mm depth temperature. The heat flux is plotted in units of $10^7\text{ W} \cdot \text{m}^{-2}$. [6]

An asymptotic model of work roll heat transfer was developed by R.E. Johnson and R.G. Keanini using a multiple time scale approach. [6] In order to validate the proposed model, a comparison between model results and experimental data was made. Angular position of the roll versus surface heat flux, surface temperature and 0.2 mm depth temperature are represented in this case as shown in Fig 2-3.

A. Pérez et al. [7] performed a computer simulation of the thermal behaviour of a work roll during hot rolling. Their model considers that the steady state is reached from dynamic conditions in such parameters as the length of the strip, the temperature variation along the length of the strip, and the temperature variation from the beginning to the end of the process. The phenomena taking place were considered at three different levels: (i) the independent cycle of the roll, (ii) rolling of a strip-rest, and (iii) a whole campaign. The three levels and their effects were then superimposed. The most interesting aspects that are referred to temperature are how boundary conditions were defined (Fig. 2-4) and the temperature evaluation in the results. In them, thermal profile to different penetrations at one cycle and at a rolling of a strip-rest; the mean temperature of the work roll for effect of strip-rest train and a whole campaign; and the decrease in temperature into the surface of the work roll in an exponential negative shape and in exponential negative and harmonica attenuation are shown.
Fig. 2-4: Angular sectors into which the work roll was divided. [7]

Fig. 2-5: Thermal profile to different penetrations: (a) one cycle and (b) a rolling of a strip-rest. [7]

Fig. 2-6: The mean temperature of the work roll for effect: (a) strip-rest train; (b) a whole campaign. [7]
Surface thermal damage to hot mill roll materials was investigated by R.D. Mercado-Solis et al. [8] using twin-disc high-temperature laboratory test rig under conditions that are relevant to those of the early stands of a hot strip rolling mill. A coupled thermo-mechanical model based on the finite element method was developed to predict the temperature distribution within the core and at the surface of the roll test samples. In that case, two diametrically opposed thermo-couples were embedded at 1 mm and 1.5 mm below the roll disc working surface. After that, sub-surface thermal cycling of the roll disc at both depths was evaluated and both situations were compared. It is interesting to advertise the low temperature of the roll at these depths whilst contact disk temperature was up to 1000 °C.

Fig. 2-7: Decrease in temperature into the surface of the work roll: (a) exponential negative, effect cycle; (b) exponential negative and harmonica attenuation. [7]

Fig. 2-8: Sub-surface thermal cycling of the roll disc test sample. Thermocouple depth: 1 mm, stock disc temperature: 1000 °C, contact load: 1.5 kN. [8]
Mohammad Abbaspour et al. [9] developed a computer model based on finite difference method under transient condition to calculate the temperature and thermal crown profile in the work roll. The model has the ability of accepting variable boundary condition in circumferential and axial direction for different cooling configurations such as using different types and numbers of nozzles and headers in different direction. The results of simulation were compared and verified with an actual rolling program result for which the temperature of a work roll was measured at Mobarakeh Steel Complex. In this case the evaluation of the temperature is exhaustive. First of all a schematic illustration of heat transfer in hot rolling roll is shown in Fig 2-11(a). After that, detailed temperatures profiles are shown in two different cases. The first one (Case 1), considering the original work roll cooling used in finishing mill to calibrate the model and determine the calibration coefficients and the second case (Case 2) is by developing a new work roll cooling using
the variable heather length for rolling of different strip. These are shown in Fig. 2-11(b) to Fig. 2-16.

![Fig. 2-11](image1.png)

**Fig. 2-11:** (a) Temperature variation in different layer of work roll for one rotation; (b) variation of the mean temperature with respect to rolling time. [9]

![Fig. 2-12](image2.png)

**Fig. 2-12:** (a) Variation of thermal crown with respect to rolling time; (b) comparison of result for current study and experimental data– Case 1. [9]
Fig. 2-13: Variation of mean temperature with respect to work roll length. [9]

Fig. 2-14: Variation of thermal crown with respect to work roll length. [9]

Fig. 2-15: Mean temperature distributions in work roll for passing 15th strip. [9]
Fig. 2-16: Mean temperature distributions in work roll for passing 25th strip. [9]

A one-cycle thermal profile in stationary conditions is always plotted in an article which is interested in temperature evaluation (Fig. 2-3, Fig. 2-5, Fig. 2-10, Fig. 2-11(a)). One of the most outstanding features of this kind of plot is the thermal profile for different penetrations in which absolutely different profiles can be observed and thermal conductivity effects, by taking notice of the position of the maximum points of those profiles, are shown (Fig. 2-5). Therefore, heat transfer conditions should be perfectly defined (Fig. 2-4).

As it is shown in the model made by A. Pérez model [7] (Fig. 2-7), temperature decreases from 540 °C to 90 °C in less than 3 mm depth, this means that in a short roll radial distance a high temperature gradient appeared. Apart from this, in same picture, a harmonica attenuation effect is shown in a depth of 6 mm approximately. This latter effect is not commonly found in literature and it is maybe pretty important in crack emergence in so far as there are multiple chances of the sign of the thermal gradient in different parts of the roll at the same time.

Other outstanding feature is the behaviour of the core temperature which is considerably slower than the behaviour of the surface temperature and this fact may causes unexpected thermal gradients. Comparison between surface behaviour and core behaviour can be found in Fig. 2-11(b), Fig. 2-13, Fig. 2-15 and Fig. 2-16. Furthermore, in Fig. 2-15 and 2-16 it can be perceived how core temperature increases with the number of worked strips until the core become the warmest part of the roll while cooling.

The dependence of temperature with the roll length has been also taken in account by Mohammad Abbaspour et al. [9] (Fig. 2-12(b), Fig. 2-13, Fig. 2-14, Fig. 2-15, Fig. 2-16) but not such critical conditions can be found at the ends of the roll, consequently it can be more appropriate doing only a 2D simulation instead of doing a 3D one.
Finally, according to these articles, it seems that reliability of a well done computer simulation remains demonstrated due to the shown accuracy in comparisons between models and real experiments.

2.3 Thermal fatigue of work roll

As Antonio Rufin et al. [10] explained, when castings or steels are used in an environment where frequent changes in temperature occur, or where temperature differences are imposed on a part, thermal stresses occur and may result in elastic and plastic strains and finally in crack formation.

Inasmuch as thermal fatigue and thermal shock are similar concepts, it is necessary to distinguish them properly in order to reach the best comprehension of the former. Thermal shock occurs under rapid temperature change conditions and results in thermal stresses that cause fracture of the material. Three main differences between thermal fatigue and thermal shock may be considered: firstly, thermal fatigue means repeated thermal cycling while thermal shock is a single application of a temperature change; secondly, physical properties such as specific heat and thermal conductivity influence the stresses developed in thermal shock, which is not the case in quasistatic thermal stress because the strain rates are high in the former; and thirdly, the stresses generated in thermal shock are high enough that fracture toughness level is important while it does not enter in thermal fatigue considerations [11].

Crack initiation and propagation

The developing thermal fatigue-crack is mainly initiated on the surface and penetrates into the interior of material; the nucleation and propagation of fatigue cracks are preferentially directed along the clustering zone of bulk carbides and graphite nodules [12].
Some investigations about fatigue cracking have indicated that the cracks may initiate at carbide eutectics due to the difference in thermal expansion coefficients, primary carbides and ferrite dendrites [13] and at graphite nodules due to their low yield strength.

**Correlation of microstructure**

Microstructure of castings has been evidenced to be highly significant for thermal fatigue life. Sunghak Lee et al. [13] gathered experimental data comparing thermal fatigue behaviour of nickel-grain cast-iron, high-chromium cast-iron and high-speed steel concluding that the latter, with the highest hardness, tensile strength and lowest volume fraction of carbides showed the longest thermal fatigue life. Other interesting conclusions they allude are the reduction of thermal fatigue life due to the decrease of compressive stress and the increase in tensile stress caused by softening that took place as fatigue cycle continued, the inverse relationship between number density of surface cracks and thermal fatigue life and the intensification of cyclic softening with an increasing exposure time to high temperatures.

**Table 2-4:** Chemical Compositions of the HSS, the Hi-Cr, and the Ni-Grain Rolls wt. %.

<table>
<thead>
<tr>
<th>Roll</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>P</th>
<th>S</th>
<th>V</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSS</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5.0</td>
<td>1.0</td>
<td>2.5</td>
<td>0.04</td>
<td>0.02</td>
<td>4.0</td>
<td>bal</td>
</tr>
<tr>
<td>Hi-Cr</td>
<td>2.8</td>
<td>1.0</td>
<td>1.07</td>
<td>15.6</td>
<td>1.28</td>
<td>1.27</td>
<td>0.034</td>
<td>0.017</td>
<td></td>
<td>bal</td>
</tr>
<tr>
<td>Ni-grain</td>
<td>3.2</td>
<td>0.83</td>
<td>0.68</td>
<td>1.93</td>
<td>3.6</td>
<td>0.32</td>
<td>0.048</td>
<td>0.016</td>
<td></td>
<td>bal</td>
</tr>
</tbody>
</table>

Other authors like Benzulce [1] performed similar work reaching similar results and also concluding that high speed steel owns high wear and thermal fatigue resistances and links
it with its relatively low carbon content resulting in hard and well dispersed carbides. However W.S. Dai [12] goes further by casting into a complex mono-casting composed of sand mold and iron mold to obtain different solidification structure distribution in the same test specimen. The obtained result was a variation of crack orientation depending on the microstructure of the zone in which grows as it is shown in Fig. 2-18.

**Fig. 2-18:** The microstructure distribution and surface crack orientation morphology of complex mono-casting specimen with sequent solidification structure. [12]

**Damage in hot rolling work rolls**

During hot rolling work rolls are subjected to successive heating and cooling conditions. Their surface is exposed to rapid temperature changes due to the contact with hot rolled material and due to cold water used for work rolls cooling. This cyclic heating/cooling conditions cause thermal fatigue which is one of the most important factors affecting the rate of surface deterioration as well as mechanical fatigue and abrasion. The surface of the working rolls is of essential meaning for the quality of hot rolled products. It influences the surface appearance as well as the transverse profile of the rolled product. The formation of firecracks has a consequence of damaging the surface of the working rolls. These defects can also be imprinted in the rolling product.

Samples from a couple of work rolls employed in a hot rolling steel strip mill were examined by scanning electron microscopy in order to study their surface by Rafael Colás et al. [1] It was found that a series of cracks developed within the rolls at the beginning of their operational cycle, these cracks followed the primary carbide network and were attributed to be caused either by thermal fatigue or by a combination of thermal fatigue and contact stress. Work rolls heated up as a result of contact with the steel strip and an oxide layer was formed on them. It was observed that oxidation preceded through the cracks, isolating healthy material with brittle layers, a characteristic which might explain the high wear rate encountered in some stands of the mill.
Advice

To improve the overall mechanical properties, including the thermal fatigue property, according to Sunghak Lee et al. [13], it is desirable to remove the segregated cell boundary carbides, to reduce the cell size to refine the carbides, and to induce better distribution of them. To establish the hot-rolling conditions, a precise estimation of the thermal fatigue property is required. Further studies are necessary on the characteristics and distribution of carbides, interpretation of fracture mechanism, and on oxidation resistance, as well as on optimum casting conditions, because the thermal fatigue property is closely related to the tensile strength, wear resistance, and fracture toughness of the rolls.

Union Electric Steel: Forged and Cast Rolls [14] in their technical service manuals give some advice in order to prevent this kind of failure in the case that the rolling mill suddenly stalls. The following procedure is recommended by Union Electric Steel in order to minimize the severity of the cracking that will result:

- As soon as possible, after rolling mill stalls, opening the roll gap to remove direct contact between the roll and the strip.
- Turning off the roll cooling water to prevent a rapid rate of cooling at the locally heated area.
- Once the strip has been removed, rotate the rolls for a minimum of 20 minutes to allow equalization of the roll surface temperature.

After this type of incident, roll should be removed from the mill for re-grinding. It is an accepted practice in many mills for rolls in the early stands displaying this type of stall band cracking not to entirely remove cracks during the grinding operation so that grinding can be only continued until the cracks appear tightly closed by eye.

In general terms, according to Union Electric Steel: Forged and Cast Rolls, if the rate of crack propagation in a given mill stand during a rolling campaign is less than the average stock removal during grinding then it is safe to leave residual cracking of this type in the barrel surface. If however the rate of crack growth is higher than the average stock removal (as can occur in the mid-position of the mill) then it is recommended that all cracking be removed. Failure to do so can result in crack growth to greater depth and even failure by spalling in a ribbon fatigue mode.

To remove all cracks from rolls operating in the later stands of the mill due to the rapid rate of crack growth that will occur is recommended.

2.4 Physical simulation of work roll thermal fatigue

Some physical simulations have been done in order to simulate the behaviour of work rolls and to obtain and study the same phenomena that appear on them.
The main purpose of the investigation of Li Chang Sheng L. et al. was the development of a method for evaluating thermal wear of rolls in hot rolling process [16]. Their simulation was composed by 2 disks (upper disk dimension is 1160 mm x 30 mm and lower disk dimension is 1160 mm x 50 mm), an induction heater able to reach temperatures higher than 900 °C, a water box and a pump and a high frequency power source. The conductor material used for their simulation was pure cooper and material of disks was high speed steel.

Fig. 2-19: Schematic illustration of thermal wear tester. [15]

Kang C.G. and Kim Y.D. determined the heat-transfer coefficient and transition thermal analysis in the direct rolling process using both experimental and finite-element method comparison [16]. They used one roll whose dimensions were 170 mm outer diameter, 130 mm inner diameter and 180 mm width; one heating plate with cartridge-type heaters inserted in it, a 10 ton hydraulic cylinder on the heating plate to simulate the effect due to contact force on the temperature distribution of the roller, four thermocouples added in machined by electric spark machining holes, a load cell setup to measure pressure and a multi-logger to read temperature measurement from thermocouples due to impossibility of measuring it directly because of rotation of the roll. The roller was made of 0.5 % carbon steel. The oil was spread on the roll surface in order to reduce friction.
Anders Persson et al. simulated and evaluated thermal fatigue cracking of hot work tool steels [17]. Physical simulation was composed by a specimen of 10 mm in diameter, 80 mm in length and a 3 mm axial hole for internal cooling; an induction unit consisted of an HF-generator and a coil, a pyrometer to monitor surface temperature and also a K-type Chromel-Alumel thermocouple to measure it and HeNe-laser in order to measure surface strain with non-contact laser speckle technique. Some variants of heat treatment of QRO 90 Supreme and Hotvar Uddeholm hot work tool steels were used as test materials. Continuous cooling was performed with silicon oil or water and also externally with argon or air.
The relationship between friction and wear of work roll and oxidation was investigated for two different environmental conditions by Garza-Montes-de-Oca N. F. and Rainforth W.M. [19] Its simulation consisted of disks of 60 mm in diameter and 16 mm in thickness cut to the final shape by spark erosion with initial surface roughness of approximately 0.40 ± 0.20 μm. The rig also had nozzles with water applied directly onto the surface of the counter disc in a drop wise fashion and a mixture dry air and water vapour produced at 85 °C injected through one of these nozzles at a rate of 600 cm³/min, RF induction heating. Temperature of the disc was controlled by means of a Rytek LT infrared optical pyrometer connected to a data acquisition system that compared the value of the set temperature against the instantaneous reading taken by the pyrometer, providing a feedback loop to give dynamic temperature control. A load of 2.5 kg was applied to the discs via cantilever resulting in a Hertzian contact pressure of 694 MPa. In this case, the material used for the discs was high speed steel that would replicate the microstructure of a commercial work roll which was heat treated in accordance with the standard commercial heat treatment cycle known to impart optimum wear properties.

Induction heating mode is one of the most popular modus operandi. It is used in most of cases in which thermal fatigue in hot-rolling rolls is pretended to be simulated however it is not obvious that induction heating could be able to reach same surface temperature.
reached in real hot rolling work roll with the same timing. Thus, thermal stress is not being as severe as it may be in the real case.

Pyrometer and laser speckle technique are interesting elements of physical simulations. The former technique and can be useful in order to get better and contrasted measurements to have better quality data. The latter may gives a good idea of the dynamic behaviour of the tested specimen, which can be useful in order to predict final status of it.

Cooling is usually achieved by using water, silicon oil, air and/or argon. All cases should be considered and which assimilate the most to real case should be used, though using the ones which sharp wear phenomena may be a good alternative in order to get knowledge about the worst working conditions.
3. Experiments

For a better understanding of materials behaviour subjected to thermal fatigue two tests using the Gleeble 1500D thermo-mechanical simulator were developed. These tests enabled a simulation of the thermal fatigue of work rolls in the case of regular rolling condition and in case of rolling mill stalls as well. The aim was to find how crack density and crack length are related to exposed temperature, contact time and the cooling method after contact (air cooling or water cooling).

3.1 Specimen

Specimens were machined from the high chromium steel work rolls. They were of cylindrical shape with a borehole in the longitudinal axis (Fig. 3-1) that enabled cooling of specimens with stream of water and air. The test cell is presented in Fig. 3-5. The reduction of the diameter in the central part of the specimen intensified the temperature gradient during the heating and cooling stage of the experiment. The temperature was controlled with thermocouples that are spot-welded in the middle of the reduced part of the specimen, (Fig. 3-5).

The chemical composition of the specimen is given in the Table 3-1.

| Table 3-1: Chemical composition of the specimen, wt. % |
|----------|----------|----------|----------|----------|
| C        | Si       | Mn       | Cr       | Ni       | Mo       |
| 2.06     | 0.73     | 0.80     | 9.60     | 2.00     | 1.00     |

Fig. 3-1: Dimensions of the specimen in millimetres.
3.2 Thermal fatigue testing

Two different tests for the laboratory assessments of the thermal fatigue resistance of work rolls were used. The first test enabled a simulation of the work roll thermal fatigue in the case of regular rolling. Furthermore, with the second test thermal fatigue of work rolls in the case of the rolling mill stalls was investigated. Both tests were implemented in a thermo-mechanical simulator of metallurgical states, the Gleeble 1500D. The real thermal fatigue cycling and stalling of the work roll were simulated by computer-controlled resistance heating and water cooling of the samples as well as air blowing was realized. Furthermore, temperature distribution in the specimen cross section was also obtained.

The cooling and emptying process was optimized using a pair of magnetic, computer-controlled valves. One valve controlled the water inlet for the quenching and the other controlled the compressed air, which was used to drive out the steam and the water from the cooling chamber. The valves were also computer-guided using the Gleeble 1500D computer that was programmed simultaneously with the program for the thermal loading of the sample. The samples were freely spanned in the working jaws of the Gleeble loading system, keeping the outer force on the samples at 0 N. The physical simulations of the roll thermal fatigue may give selective results of the influence of the testing parameters to the initiation and growth of the cracks.
3.2.1 Temperature distribution in the specimen cross section

Three thermocouples for the temperature measurement and control were welded in three different depths (Fig. 3-4), 1 mm from the outer surface, 0.7 mm from the outer surface and on the outer surface (2 mm from the quenching surface). The samples were first heated and after that cooled by the water cooling that lasted for 0.5 s and air for 0.5 s after achieving the maximum temperature. Seven tests were performed. Some cycle repetitions were performed and then temperature was maintained for 15 or 60 seconds in order to know the thermal profile through the specimen.

Experimental conditions are detailed in Table 3-2

![Diagram showing the position of thermocouples](image)

**Fig. 3-4:** Position of thermocouples. Dimensions in millimeters.
**Fig. 3-5:** Test cell with specimen and three welded thermocouples.

**Table 3-2:** Experimental conditions in the temperature distribution experiments.

<table>
<thead>
<tr>
<th>Test</th>
<th>Temp. (°C)</th>
<th>Cycles</th>
<th>Hold. time (s)</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>51A</td>
<td>500</td>
<td>20</td>
<td>15</td>
<td>air</td>
</tr>
<tr>
<td>52A</td>
<td>500</td>
<td>10</td>
<td>15</td>
<td>water</td>
</tr>
<tr>
<td>52B</td>
<td>500</td>
<td>10</td>
<td>60</td>
<td>water</td>
</tr>
<tr>
<td>61A</td>
<td>600</td>
<td>10</td>
<td>15</td>
<td>air</td>
</tr>
<tr>
<td>62A</td>
<td>600</td>
<td>10</td>
<td>15</td>
<td>water</td>
</tr>
<tr>
<td>71A</td>
<td>700</td>
<td>10</td>
<td>15</td>
<td>air</td>
</tr>
<tr>
<td>72A</td>
<td>700</td>
<td>10</td>
<td>15</td>
<td>water</td>
</tr>
</tbody>
</table>
Fig. 3-6: Example of a programmed test. Line 13: 3 s heating until TC1 (Thermocouple 1) reaches 500 °C. Line 14: Stop heating in 0.1 s. Line 15 & 16: Water cooling for 0.5 s. Line 17: Stop blowing water. Line 18 & 19: Air cooling for 0.5 s. Line 20: Stop blowing air. Line 21: Wait for 0.2 seconds and go to number 13 (10 times repetition) Line 22: Heating until TC1 reaches 500 °C. Line 23: Hold temperature for 15 s.

3.2.2 Thermal fatigue testing

Two different series of tests were carried out in the laboratory. In the first one, specimens were heated to three different temperatures, 500 °C, 600 °C and 700 °C, and then rapidly cooled down with water. This operation was repeated for 500 cycles. In the second one, specimens were also heated to 500 °C, 600 °C and 700 °C; then rapidly cooled down with water and then, after 500 cycles, temperature was maintained. For the lowest temperature (500 °C), the cooling rate was at 175 K/s, and at the highest temperature (700 °C), it increased to 250 K/s.
The thermocouple for the temperature measurement and control was spot-welded in the middle of the external wall of the samples (2 mm from the quenching surface) (Fig. 3-7). The samples were heated and cooled by the water quenching that lasted for 0.5 s and air for 0.5 s after achieving the maximum temperature. Fifteen specimens were prepared. 500 cycle repetitions were performed and then temperature was maintained at three different holding times: 0 s, 15 s and 60 s for each case to monitor the onset and growth of the thermal cracking on samples’ tested surfaces.

Experimental conditions are detailed in Table 3-3.
Table 3-3: Experimental conditions in the thermal fatigue testing experiments.

<table>
<thead>
<tr>
<th>Test</th>
<th>Temp. (°C)</th>
<th>Cycles</th>
<th>Hold. time (s)</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>0S 500</td>
<td>500</td>
<td>500</td>
<td>0</td>
<td>air</td>
</tr>
<tr>
<td>T1A 500</td>
<td>500</td>
<td>500</td>
<td>15</td>
<td>air</td>
</tr>
<tr>
<td>T1B 500</td>
<td>500</td>
<td>500</td>
<td>60</td>
<td>air</td>
</tr>
<tr>
<td>T2A 500</td>
<td>500</td>
<td>500</td>
<td>15</td>
<td>water</td>
</tr>
<tr>
<td>T2B 500</td>
<td>500</td>
<td>500</td>
<td>60</td>
<td>water</td>
</tr>
<tr>
<td>0S 600</td>
<td>600</td>
<td>500</td>
<td>0</td>
<td>air</td>
</tr>
<tr>
<td>T1A 600</td>
<td>600</td>
<td>500</td>
<td>15</td>
<td>air</td>
</tr>
<tr>
<td>T1B 600</td>
<td>600</td>
<td>500</td>
<td>60</td>
<td>air</td>
</tr>
<tr>
<td>T2A 600</td>
<td>600</td>
<td>500</td>
<td>15</td>
<td>water</td>
</tr>
<tr>
<td>T2B 600</td>
<td>600</td>
<td>500</td>
<td>60</td>
<td>water</td>
</tr>
<tr>
<td>0S 700</td>
<td>700</td>
<td>500</td>
<td>0</td>
<td>air</td>
</tr>
<tr>
<td>T1A 700</td>
<td>700</td>
<td>500</td>
<td>15</td>
<td>air</td>
</tr>
<tr>
<td>T1B 700</td>
<td>700</td>
<td>500</td>
<td>60</td>
<td>air</td>
</tr>
<tr>
<td>T2A 700</td>
<td>700</td>
<td>500</td>
<td>15</td>
<td>water</td>
</tr>
<tr>
<td>T2B 700</td>
<td>700</td>
<td>500</td>
<td>60</td>
<td>water</td>
</tr>
</tbody>
</table>

Each cycle was composed of four phases: resistance heating (3 s), water cooling (0.5 s) and cooling of the specimen with air (0.5 s), holding time (0.2 s) all in duration of 4.2 s.

![Simulated thermal cycle](image)  
**Fig. 3-8:** Simulated thermal cycle.
Fig. 3-9: Measured temperature (a) 600 °C, holding time $t = 15$ s, free air cooling; (b) 500 °C, holding time $t = 60$ s, forced water cooling.

3.3 Light and scanning electron microscopy

Specimen were cut in the longitudinal and in the transverse direction and set into an epoxy potting compound. They were prepared for metallographic examination by polishing for the crack density and crack length determination and by additional etching where grain structure is of interest. Optical microscopy was applied to determinate the crack density, average length of the cracks, maximal length of the cracks and present phases (Olympus bx61). Electron scanning microscope SEM JEOL-5610 with the energy dispersive X-ray spectroscopy (SEM-EDS) was used for the chemical composition determination.
Fig. 3-10: Observed transversal and longitudinal sections in each specimen.

Fig. 3-11: Specimen preparation for applying microscopy.
4. Finite Elements Method Simulations

In order to get a good knowledge about the rolls behaviour when the rolling mill suddenly stalls during rolling of hot slabs, finite elements method simulations about this particular case were performed. The studied cases when rolling mill stalls were as follows:

- **Case 1**: Simulations were performed for three different slabs with 200 mm, 100 mm and 20 mm in thickness using 900 °C, 1000 °C, 1100 °C and 1200 °C as initial slab’s temperature. The target was the surface temperature.

- **Case 2**: Simulations were performed for three different slabs with 200 mm, 100 mm and 20 mm in thickness using 900 °C, 1000 °C, 1100 °C and 1200 °C as initial slab’s temperature and followed by air and water cooling. The target was the surface temperature.

- **Case 3**: Three different conditions were studied: In first condition, a 200 mm slab with 1200 °C as initial temperature was simulated. In second condition, a 100 mm slab with 1100 °C as initial temperature was simulated. In third condition, a 20 mm slab with 1000 °C as initial temperature was simulated. The target was the temperature profile below the surface of the roll.

Simulations were performed using NSC.SuperForm software used for finding solutions to manufacturing problems including hot and cold (open or closed) forging, extrusion, rolling, blanking, cogging, cladding, thick sheet bending, riveting, spin forming, orbital forming, cutting, and die stress analysis.
4.1 Material properties

Applied material properties for the simulated roll were taken from product catalogue of Valji Company [19]. Simulations were with the use of the physical values given in Fig. 4-1.
Fig. 4-1: (a) Thermal conductivity vs. temperature; (b) Modulus of elasticity vs. temperature; (c) Thermal expansion vs. temperature; (d) Specific heat vs. temperature.

4.2 Simulation parameters and conditions

In tables (Table 4-1, Table 4-2) description and parameters of performed hot rolling simulations are presented:

<table>
<thead>
<tr>
<th>Table 4-1: Simulations parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab reduction</td>
</tr>
<tr>
<td>Rolls diameter</td>
</tr>
<tr>
<td>Rolls initial temperature</td>
</tr>
<tr>
<td>Rolls angular velocity</td>
</tr>
<tr>
<td>Rolls friction coefficient</td>
</tr>
<tr>
<td>Environment temperature</td>
</tr>
<tr>
<td>Convection coefficient to environment</td>
</tr>
<tr>
<td>Rolls contact heat transfer coefficient</td>
</tr>
<tr>
<td>Water temperature</td>
</tr>
</tbody>
</table>
Table 4-2: Simulations conditions.

<table>
<thead>
<tr>
<th>First case</th>
<th>Second case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab thickness</td>
<td>200 mm, 100 mm, 20 mm</td>
</tr>
<tr>
<td>Slab temperatures</td>
<td>900 °C, 1000 °C, 1100 °C, 1200 °C</td>
</tr>
<tr>
<td>Cooling method</td>
<td>none</td>
</tr>
<tr>
<td>Rolling time</td>
<td>1.22 s</td>
</tr>
<tr>
<td>Contact time</td>
<td>300 s</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Second case</td>
<td></td>
</tr>
<tr>
<td>Slab thickness</td>
<td>200 mm, 100 mm, 20 mm</td>
</tr>
<tr>
<td>Slab temperatures</td>
<td>900 °C, 1000 °C, 1100 °C, 1200 °C</td>
</tr>
<tr>
<td>Cooling method</td>
<td>air, water</td>
</tr>
<tr>
<td>Rolling time</td>
<td>1.22 s</td>
</tr>
<tr>
<td>Contact time</td>
<td>60 s</td>
</tr>
<tr>
<td>Releasing time</td>
<td>5 s</td>
</tr>
<tr>
<td>Air cooling time</td>
<td>1195 s</td>
</tr>
<tr>
<td>Water cooling time</td>
<td>295 s</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Third case</td>
<td></td>
</tr>
<tr>
<td>Cooling method</td>
<td>none</td>
</tr>
<tr>
<td>Rolling time</td>
<td>1.22 s</td>
</tr>
<tr>
<td>Contact time</td>
<td>300 s</td>
</tr>
<tr>
<td><strong>Condition 1</strong></td>
<td></td>
</tr>
<tr>
<td>Slab thickness</td>
<td>200 mm</td>
</tr>
<tr>
<td>Slab temperature</td>
<td>1200 °C</td>
</tr>
<tr>
<td><strong>Condition 2</strong></td>
<td></td>
</tr>
<tr>
<td>Slab thickness</td>
<td>100 mm</td>
</tr>
<tr>
<td>Slab temperature</td>
<td>1100 °C</td>
</tr>
<tr>
<td><strong>Condition 3</strong></td>
<td></td>
</tr>
<tr>
<td>Slab thickness</td>
<td>20 mm</td>
</tr>
<tr>
<td>Slab temperature</td>
<td>1000 °C</td>
</tr>
</tbody>
</table>
4.3 Geometrical description

In Fig. 4-2 the three studied geometries with finite elements method simulations are shown. Geometry only depended on the slab thickness given that work roll was the same in all cases.

**Fig. 4-2:** Dimensions in millimetres of simulation for the three different studied slab thickness: (a) 200 mm; (b) 100 mm; (c) 20 mm.
4.3.1 First case

First case was performed as the description below. Simulation consisted in 1.22 s of rolling time and 5 min (300 s) contact time with no movement between rolls and slab. These simulations were performed at 900°C, 1000°C, 1100°C and 1200°C for each slab thickness: 200 mm, 100 mm and 20 mm. In this case surface temperature of the roll was calculated in order to find initial slab’s temperature and slab’s thickness dependence. Surface temperature was calculated in one of the maintained contact nodes.

![Diagram](a) (b)

**Fig. 4-3:** Steps of the first case simulation. First stage consisted of 1.22 s of common rolling (a); until stalled position was reached (b). Then, rolling mill was stopped and contact was maintained for 300 s.

4.3.2 Second case

Second case was performed as the description below. Simulation consisted of 1.22 s of rolling time, 60 s of contact with no movement between rolls and slab, 5 s to release roll from slab and cooling. Two ways of cooling were used: 20 min of air cooling (1195 s) and 5 min of water cooling (295 s) These simulations were performed at 900°C, 1000°C, 1100°C and 1200°C for each slab thickness: 200 mm, 100 mm and 20 mm. In this case surface temperature of the roll was calculated in order to know the different behaviour of roll surface in both cooling conditions. Surface temperature was calculated in one of the maintained contact nodes.
Fig. 4-4: Steps of second case simulation. First stage consisted of 1.22 s of rolling time (a); until stalled position was reached (b). Then, rolling mill was stopped and the contact time was maintained for 60 s. After that rolls and slab were separated (c). This stage took 5 s. Finally rolls were cooled down by using air during 20 min or water during 5 min (d).

4.3.3 Third case

In third case, timing was the same as in first case. These simulations were performed at 1000 °C for 20 millimetres slab thickness, 1100 °C for 100 millimetres slab thickness and 1200 °C for 200 millimetres slab thickness. In this case surface temperature of the roll was calculated in order to have better knowledge about the temperature profile below the roll’s surface. Temperature was calculated in one of the maintained contact nodes and adjacent nodes in radial direction.
5. Results and discussion

5.1 Crack initiation and propagation

During testing, thermal fatigue cracks appeared on all of the specimens (Fig. 5-1). Cracks started to grow on the cooled surface. The primary carbides (ledeburite) are the main sources of cracks initiation due to difference in temperature expansion coefficient and lower ductility in comparison with the martensite—bainite matrix. Cracks propagated along the ledeburite boundaries or even through the hard and brittle grains of ledeburite. No crack propagation through the matrix was observed.

![Micrographs of cracks.](image)

The internal surfaces of crack oxidize during thermal fatigue. Oxides act as a wedge in the cracks while the volume of the oxide is larger than the volume of the matrix material. They accelerate the crack growth. Since the most significant oxidation of the steel occurs at high temperatures the length of cracks increase with the increasing temperature. SEM EDS was used to determine the chemical composition of the base material and of the crack. Chemical composition of the oxide material which has filled up the crack (Fig. 5-2(b), spot 1, 2), carbide (ledeburite) (Fig. 5-2(b), spot 3) and of the martensite—bainite matrix material (Fig. 5-2(b), spot 4) is given in the Table 5-1.

SEM EDS analysis indicated the presence of oxygen in cracks. The material which has filled up the crack (Fig. 5-2(b), spot 1 and 2) contains approximate 2.1 wt.% of O. This confirms the oxidation of the crack surface. The ledeburite (spot 3) consists of approximate 48 wt.% of Cr, 46 wt.% of Fe, 2 wt.% of Mo and 1.7 wt.% of V.
**Table 5-1**: Chemical composition of the analysed spots (see Fig. 5-2), wt. %.

<table>
<thead>
<tr>
<th></th>
<th>Spot 1</th>
<th>Spot 2</th>
<th>Spot 3</th>
<th>Spot 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>2.15</td>
<td>2.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>0.33</td>
<td></td>
<td></td>
<td>0.49</td>
</tr>
<tr>
<td>Cr</td>
<td>39.50</td>
<td>3.07</td>
<td>48.27</td>
<td>7.97</td>
</tr>
<tr>
<td>Mn</td>
<td>0.983</td>
<td>0.56</td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>Fe</td>
<td>53.72</td>
<td>92.18</td>
<td>45.99</td>
<td>88.50</td>
</tr>
<tr>
<td>Ni</td>
<td>1.32</td>
<td></td>
<td></td>
<td>2.01</td>
</tr>
<tr>
<td>Mo</td>
<td>0.41</td>
<td>2.19</td>
<td></td>
<td>0.58</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td>1.88</td>
</tr>
<tr>
<td>V</td>
<td>1.01</td>
<td></td>
<td></td>
<td>1.67</td>
</tr>
<tr>
<td>Ca</td>
<td>0.55</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5-2**: (a) SEM micrographs of the investigated crack; (b) spots of the analyses.

At higher temperature the cracks can link together and subsequent spalling of roll surface fragments may occur (Fig. 5-3)
5.2 Crack density and crack length

Optical microscopy was applied to measure the cracks length. The number of cracks, crack density, average length of the cracks and maximal length of the cracks are given in Table 5-2.
Table 5-2: Results of first series of experiments.

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of cracks</th>
<th>Density of cracks (cracks/mm)</th>
<th>Mean length (µm)</th>
<th>Maximal length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0S 500</td>
<td>175</td>
<td>6.21</td>
<td>30</td>
<td>117</td>
</tr>
<tr>
<td>T1A 500</td>
<td>244</td>
<td>8.85</td>
<td>30</td>
<td>116</td>
</tr>
<tr>
<td>T1B 500</td>
<td>200</td>
<td>7.20</td>
<td>26</td>
<td>156</td>
</tr>
<tr>
<td>T2A 500</td>
<td>238</td>
<td>8.57</td>
<td>32</td>
<td>108</td>
</tr>
<tr>
<td>T2B 500</td>
<td>214</td>
<td>7.65</td>
<td>32</td>
<td>173</td>
</tr>
<tr>
<td>0S 600</td>
<td>155</td>
<td>7.19</td>
<td>39</td>
<td>400</td>
</tr>
<tr>
<td>T1A 600</td>
<td>161</td>
<td>7.20</td>
<td>40</td>
<td>247</td>
</tr>
<tr>
<td>T1B 600</td>
<td>192</td>
<td>8.58</td>
<td>37</td>
<td>223</td>
</tr>
<tr>
<td>T2A 600</td>
<td>*</td>
<td>7.40</td>
<td>38</td>
<td>175</td>
</tr>
<tr>
<td>T2B 600</td>
<td>229</td>
<td>9.89</td>
<td>30</td>
<td>213</td>
</tr>
<tr>
<td>0S 700</td>
<td>213</td>
<td>7.62</td>
<td>81</td>
<td>953</td>
</tr>
<tr>
<td>T1A 700</td>
<td>214</td>
<td>7.60</td>
<td>66</td>
<td>1000</td>
</tr>
<tr>
<td>T1B 700</td>
<td>243</td>
<td>8.69</td>
<td>56</td>
<td>770</td>
</tr>
<tr>
<td>T2A 700</td>
<td>256</td>
<td>9.15</td>
<td>56</td>
<td>1009</td>
</tr>
<tr>
<td>T2B 700</td>
<td>256</td>
<td>9.35</td>
<td>60</td>
<td>870</td>
</tr>
</tbody>
</table>

With the use of STATISTICA software the histograms of the crack length of the tested specimens were obtained (Fig. 5-5, Fig. 5-6 and Fig. 5-7).
Fig. 5-5: Histogram of the crack length in micrometers in the specimens heated to 500 °C. Graphics are ordered as: (a) 0S; (b) T1A; (c) T1B; (d) T2A; (e) T2B.

Horizontal edges are divided in ranges of cracks length. Vertical edges indicate the number of cracks that belong to this range. For example, at 500 °C and experimental conditions 0S (Fig. 5-5(a)), tested specimen has around 55 cracks which length is between 10 μm and 20 μm.

Crack-length histograms of specimens heated to 500 °C have all approximately the same shape. Most of cracks are between 0 μm and 30 μm long and after 20-30 μm range, number of cracks tends to gradually decrease as length increases. Longest crack appeared in test T2B and it was between 170 μm and 180 μm long.
Fig. 5-6: Histogram of the crack length in micrometers in the specimens heated to 600 °C. Graphics are ordered as: (a) 0S; (b) T1A; (c) T1B; (d) T2A; (e) T2B.

As in the previous case, crack-length histograms of specimens heated to 600°C have all approximately the same shape except in test T2A in which less data was taken. Most of cracks are between 0 μm and 30 μm long and after 20-30 μm range, number of cracks tends to gradually decrease as length increases. Longest crack appeared in test 0S and it was between 390 μm and 400 μm long.
Crack-length histograms of specimens heated to 700°C have all also similar shape. As both previous cases, most of cracks are between 0 μm and 30 μm long and then number of cracks tends to gradually decrease as length increases. Longest crack appeared in test T2A and it was between 1000 μm and 1010 μm long, but tests 0S and T1A have also similar length longest cracks and they are longer than 950 μm.

Matrix-shape graphic relating maximal cracks length and density of cracks with temperature and holding time is presented in Fig. 5-8. It was obtained by using Minitab software.
Fig. 5-8: Matrix-shape graphic of maximal cracks length and density of cracks versus temperature and holding time with regression line categorized in air cooling and water cooling.

A clear strong dependency relation between maximal length of cracks and temperature appears in Fig. 5-8. Relation between density of cracks and temperature or holding time is not strongly noticeable but increasing tendency is shown. Furthermore, density of cracks seems to depend on the cooling method: water cooling tends to increase the number of cracks compared with air cooling. No clear relation can be appreciated between maximal crack length and holding time. Despite there is no evidence about the linear dependence of data, linear regression has been chosen as relevant enough by working with the hypothesis that the correct regression function should be injective.
Fig. 5-9: Percentage histogram of cracks length categorized in air cooling and water cooling at temperatures (a) 500 °C; (b) 600 °C; (c) 700 °C.

Major part of cracks are in the range from 0 μm to 30 μm in Fig. 5-9. They represent about 60% of the total amount of all measured cracks. Nearly 30% of all cracks are in the range of 20 μm. The majority of smallest cracks (~10 μm) appeared in the case of water cooling and the majority of longest cracks appeared in the case of the air cooling. In the range between the smallest and the longest cracks, no noticeable difference of cracks length distribution according the cooling medium are established. Nevertheless, these histograms show clearly how an increase of the temperature results in an increase of the percentage of longer cracks and, furthermore, percentage of longer cracks is higher by using air cooling than by using water cooling (This fact is appreciated in last range “>100 μm”).
Fig. 5-10: Percentage histogram of cracks length at 0 s, 15 s and 60 s holding time at temperatures (a) 500 °C; (b) 600 °C; (c) 700 °C.

No clear effect in cracks distribution due to holding time appears in Fig 5-10.
The mean length of cracks and crack density of each experiment are presented in the next figures (Fig. 5-11 to Fig. 5-16).

Fig. 5-11: Average cracks length of 500 °C tests.

Fig. 5-11 shows similar mean length of cracks in all experimental conditions at 500 °C. In this case, 60 s holding time and air cooling caused the shortest cracks.

Fig. 5-12: Average cracks length of 600 °C tests.

Tests at 600 °C show also similar crack mean length. A longer holding time does not result in a longer mean length. Water cooling causes in this case shorter cracks than air cooling.
In this last figure (Fig. 5-13), length differences are more noticeable. Base test created longer cracks. Longer holding time had no effect in mean length. No clear effect of cooling down with water on mean crack length is concluded from 700 °C test.

Fig. 5-14: Crack density of 500 °C tests.

Fig. 5-14 shows higher crack density when temperature is held. In this case a longer temperature holding time produced less density of cracks. No conclusion can be made about water cooling or air cooling.
Tests at 600 °C caused a proportional relation between temperature holding time and crack density. Water also caused a higher density of cracks.

Similar conclusions than tests at 600 °C can be made from Fig. 5-16 about 700 °C tests. In this case holding temperature for 15 s seems not to have a relevant importance but holding temperature for 60 s caused higher crack density as well as water cooling caused also higher crack density than air cooling.
As it was expected, maximal crack length increases when temperature increases in every single experiment. At the temperature of 500 °C, the maximal crack lengths when holding time is 0 s (0S) or 15 s (T1A, T2A) are really similar, while it is higher when holding time is 60s (T1B, T2B). At the temperature of 600 °C, maximal crack length appears at 0 s holding time (0S). 60 s holding time cases (T1B, T2B) have similar maximal crack lengths while 15 s holding time and air cooling (T1A) shows larger crack than same holding time and water cooling (T2A). At the temperature of 700 °C, maximal length increases when holding time increases \( l(0S) < l(T1A) < l(T2A) \) and \( l(T1B) < l(T2B) \). Furthermore, shorter maximal cracks appear when cooling down with water (T1B, T2B).
5.3 Temperature evaluation in the specimen

To evaluate the used thermal fatigue test in consideration to the real thermal fatigue conditions of the work rolls, the temperature evolution in the specimen cross-section was measured. In Fig. 5-18, Fig. 19, Fig. 20 and Fig. 5-21 different aspects of the specimen temperature profile are presented.

![Graph](image)

**Fig. 5-18:** Temperature profile of specimen heated to 500 °C as programmed temperature and air-cooled.

![Graph](image)

**Fig. 5-19:** Temperature profile of specimen heated to 500 °C as programmed temperature and air-cooled. Detail of the maximum temperature of each depth.
Fig. 5-20: Temperature profile of specimen heated to 500 °C as programmed temperature and air-cooled. Detail of one complete cycle.

![Graph showing temperature profile.]

When specimen is expected to reach 500 °C, in the outer surface it reaches 490°C, in one point 0.7 mm below the surface it reaches around 510 °C and in one point 1 mm below the surface it reaches 520 °C (see Fig. 5-19). In 700 °C case, these reached temperatures are around 685 °C, 705 °C and 725 °C respectively. In Fig. 5-20 the thermal behaviour in the three different measured points for one cycle is presented. The outer surface is the last to be heated and the last to be cooled down.

Specimen was heated by using alternating current. Therefore a skin effect phenomenon may take place. From this point of view, the highest temperature should appear in the surface layers of the specimen. But due to heat transfer from the outer surface of the
specimen due to convection and radiation the temperature at the outer surface \((T_1)\) was lower as in the depth of 0.7 mm. This is the possible explanation to the temperature distribution at different depths in the specimen. The temperature distribution in the work roll is non homogeneous as well. During heating the maximum temperature of the work roll is at surface, during cooling the maximum temperature moved in the work roll core direction.

5.4 FEM simulation of work roll temperature

With the FEM simulations, following results were obtained: influence of roll piece thickness and its initial temperature on work roll surface temperature; influence of cooling conditions on work roll surface temperature and temperature profile of work rolls.

5.4.1 Influence of roll piece thickness and its initial temperature on work roll surface temperature

Images below (Fig. 5-22 to Fig. 5-24) show the roll surface temperature in case of rolling mill stalls when slab initial temperatures were 1200 °C, 1100 °C, 1000 °C and 900 °C. These results are presented for three different slab thicknesses: 200 mm, 100 mm and 20 mm.

When slab thickness is 200 mm, all thermal curves reaches their maximal temperature at around 10 s, and they are 878 °C, 834 °C, 766 °C and 644 °C respectively.

![Graph showing temperature vs. time for different initial temperatures and slab thicknesses.]

**Fig. 5-22:** Surface temperature for 200 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C and 1200 °C.

At initial temperature of 1200 °C, 1100 °C, 1000 °C and 900 °C, and the slab thickness of 100 mm the roll surface temperature reaches 894 °C at 20 s, 838 °C at 12 s, 764 °C at 10 s, and 707 °C at 6 s (Fig 5-23).
Fig. 5-23: Surface temperature for 100 mm slab thickness exposed to four different initial temperatures: 900°C, 1000°C, 1100°C and 1200°C.

Fig. 5-24: Surface temperature for 20 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C and 1200 °C.

In the analyzed time, Fig. 5-22, Fig. 5-23 and Fig. 5-24 show the different behaviour of the temperature related to the slab thickness at one contact point of the outer surface of a high chromium roll at different slab temperatures. When slab is thick enough (200 mm), roll contact point reaches a certain temperature and maintains it for more than 5 min. When slab thickness is 100 mm, maximum reached temperature is almost the same but roll surface does not maintain the temperature but it decreases slowly. When surface thickness is 20 mm thick, roll reaches lower temperatures when same slab initial temperatures and starts cooling down faster.
5.4.2 Influence of cooling conditions on work roll surface temperature

Images below show the roll surface temperature in case of rolling mill stalls and after one minute contact, roll surface was cooled down by air or by water. Slab initial temperature was 1200 °C, 1100 °C, 1000 °C and 900 °C. These results are presented for three different slab thicknesses: 200 mm, 100 mm and 20 mm.

![Graph showing roll surface temperature for 200 mm slab thickness](image1)

**Fig. 5-25:** Roll surface temperature for 200 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C and 1200 °C and cooled down by air.

![Graph showing roll surface temperature for 100 mm slab thickness](image2)

**Fig. 5-26:** Roll surface temperature for 100 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C and 1200 °C and cooled down by air.
Fig. 5-27: Roll surface temperature for 20 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C and 1200 °C and cooled down by air.

Fig. 5-28: Roll surface temperature for 200 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C and 1200 °C and cooled down by water.
Fig. 5-29: Roll surface temperature for 100 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C, and 1200 °C and cooled down by water.

Fig. 5-30: Roll surface temperature for 20 mm slab thickness exposed to four different initial temperatures: 900 °C, 1000 °C, 1100 °C, and 1200 °C and cooled down by water.

Temperature in the contact point of the high chromium steel roll before cooling down has the same behaviour as it was seen before. From Fig. 5-25 to Fig. 5-30, the faster decreasing of temperature caused by water cooling compared to air cooling is observed.

5.5 Temperature Profile of Work Rolls

The images below show the roll thermal profile in case of rolling mill stalls in three different conditions: Initial slab temperatures are 1200 °C, 1100 °C, 1000 °C, and slab thicknesses are 200 mm, 100 mm and 20 mm respectively.
As it is presented in Fig 5-31, when slab is 200 mm thick temperature at each depth tends to increase at least during first 300 s.

In Fig. 5-32 temperature starts decreasing after some seconds when slab thickness is 100 mm. From the surface to 12 mm depth, maximal temperature is reached at 76 s, 110 s, 150 s, 177 s and 205 s respectively.
Fig. 5-33: Roll temperature profile for 20 mm slab thickness exposed to 1000 °C at roll depths of 0 mm, 3 mm, 6 mm, 9 mm and 12 mm.

In Fig. 5-33 temperature starts decreasing after few seconds when slab thickness is 20 mm. From the surface to 12 mm depth, maximal temperature is reached at 10 s, 16 s, 22 s, 31 s and 38 s respectively.

The different behaviour of temperature depending on the depth of the roll is shown in Fig. 5-28 to Fig 5-30. The thinnest slab temperature has different behaviour due to minor heat capacity because of its thickness. Temperature seems to converge to the same values at all depths. Furthermore, characteristic points of curves are reached later while calculated point is deeper, for example, maximum of curves in Fig. 5-33 are clearly reached earlier by the point in the outer surface than its analogous at 12 mm depth.
6. Conclusions

In order to get better understanding about high chromium steel roll cracks nucleation and their growth for the case of rolling mill stalls, laboratory tests and finite element method simulations were performed. Laboratory tests were implemented in a thermo-mechanical simulator of metallurgical states, the Gleeble 1500D. Simulations were carried out by using software, NSC SuperForm.

Several experimental tests were performed. Specimens were tested in thermal cycling conditions with different temperatures, cooling method (air cooling or water cooling) and temperature holding time after certain number of cycles. Thermal profile through the specimen was also investigated.

Several hot rolling cases simulations were performed by using finite elements method. The case of rolling mill stalls was calculated for different initial slab temperatures, thickness and with different cooling methods (air cooling or water cooling). Thermal profile until 12 millimetres below the roll surface was also calculated. The results are as follows:

a) General
- Major part of cracks was in the range from 0 μm to 30 μm. They represented about 60 % of the total amount of all measured cracks. One third of all cracks were in the range of 20 μm. The majority of smallest cracks (~ 10 μm) appeared in the case of water cooling.
- Amount of longer cracks (l > 100 μm ) increased with increasing temperature from 1 % at the temperature of 500 °C to 13 % at the temperature of 700 °C. More (about 2 %) cracks appeared in the case of air cooling.
- Maximal length of cracks increased with increasing temperature and slightly decreased with increasing holding time. No influence of the cooling type was noticed.
- Density of cracks increased when increasing temperature and when increasing holding time. The density of crack was higher in the case of water cooling.

b) Simulation of regular rolling
- Average cracks length increased when increasing temperature from 30 μm at the temperature of 500 °C to 81 μm at the temperature of 700 °C.
- Cracks density increased when increasing temperature from 6.21 cracks/mm at the temperature of 500 °C to 7.62 cracks/mm at the temperature of 700 °C.

c) Simulation of rolling mill stalls
- Average cracks length at the case of 15 s holding time was in general longer than in the case of 60 s holding time regarding the type of cooling. No clear relation between the cooling method and the crack length was found.
• Cracks density was higher in the case of water cooling as in the case of air cooling.

d) Temperature evolution in the specimen
• Temperature field in the specimen cross-section was not uniform. In the heating period the lowest temperature was at the outer surface and the highest in the layer 0.7 mm beneath the outer surface.

e) Slab thickness
• Slab thickness had a crucial role in the work roll surface temperature evolution in time.

These results are quite relevant regarding few laboratory tests that were carried out. For more accurate answer on how the cooling medium influences initiation and propagation of cracks in the work rolls more laboratory test should be performed.
7. References


