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MECHANISMS OF LARGE PARTICLE SPALLATION IN THERMAL FATIGUE OF HIGH-CHROMIUM TOOL STEEL

MEHANIZMI LUŠČENJA VELIKIH DELCEV PRI TOPLOTNEM UTRUJANJU ORODNEGA JEKLA Z VISOKO VSEBNOSTJO KROMA

Jaka Burja[1,2,3]*, Goran Kugler[2], Milan Terčelj[2], David Bombač[2]
[1]Institute of Metals and Technology, Lepi Pot 11, 1000 Ljubljana, Slovenia
[2]Faculty of Natural Sciences and Engineering, University of Ljubljana, Aškerčeva cesta 12, 1000 Ljubljana, Slovenia
[3]College of Industrial Engineering, Mariborska Cesta 2, 3000 Celje, Slovenia

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High-chromium steels used for hot rolling work rolls are exposed to severe cyclic thermal and mechanical loads, which often lead to unexpected early failure due to large particle spalling. This study investigates the mechanisms of oxidation-assisted cracking that promote early spallation under thermal fatigue conditions. Laboratory tests were performed on centrifugally cast high-chromium steel using a thermomechanical simulator to replicate harsh oxidation and cyclic heating environments. Microstructural analysis revealed that eutectic carbides and chromium-depleted regions are particularly susceptible to oxidation, accelerated crack initiation and growth. Three distinct modes of crack linking were identified as critical pathways for large particle spalling: (Mode 1) direct linking of radial cracks, (Mode 2) linking of radial cracks via lateral cracks, and (Mode 3) linking of radial cracks via oxidized eutectic carbides. The results highlight combined influence of oxidation, carbide network arrangement, and thermal stress on early spallation of large particles, providing new insights into roll surface degradation and potential directions for improving roll lifetime in industrial hot rolling.

Keywords: thermal fatigue, high-Cr steel, oxidation-assisted cracking, large particle spalling

Visokokromova jekla, ki se uporabljajo za delovne valje so pri vročem valjanju izpostavljena močnim cikličnim toplotnim in mehanskim obremenitvam, kar pogosto vodi do nepričakovane zgodnje odpovedi zaradi luščenja velikih delcev. Ta študija raziskuje mehanizme oksidacijsko pospešenega pokanja, ki vodijo v zgodnje krušenje velikih delcev pri pogojih toplotnega utrujanja. Laboratorijski testi smo izvedli na vzorcih centrifugalno litega visokokromovem jekla z uporabo termomehanskega simulatorja. Tako smo simulirali ostre pogoje oksidacije in cikličnega segrevanja. Mikrostrukturna analiza je razkrila, da so evtektični karbidi in območja z zmanjšano vsebnostjo kroma ob karbidni mreži še posebej občutljiva na oksidacijsko pospešeno rast razpok. Identificirali smo tri različne načine povezovanja razpok, ki vodijo v krušenje velikih delcev: (način 1) neposredno povezovanje radialnih razpok, (način 2) povezovanje radialnih razpok z lateralnimi razpokami in (način 3) povezovanje radialnih razpok preko oksidiranih evtektičnih karbidov. Rezultati kažejo na velik pomen skupnega vpliva oksidacije, razporeditve karbidne mreže in temperaturnih napetosti za zgodnje krušenje velikih delcev. Članek daje nov uvid v površinsko degradacijo valjev in potencialne usmeritve za izboljšanje življenjske dobe valjev pri industrijskem vročem valjanju.

Ključne besede: toplotno utrujanje, visokokromovo jeklo, oksidacijsko pospešeno pokanje, krušenje velikih delcev

1 INTRODUCTION

In hot rolling, work rolls are subjected to high cyclic thermal, mechanical and tribological loads as well as chemical degradation. The most common unexpected early failure of work rolls are spalling of large particles from the work roll surface and roll surface breakdown. Such failures require replacement of the work rolls, which increases production costs.[1–4] The phenomena of early spalling of large particles are still not adequately explained, and recent studies suggest that it is probably related to oxidation.[1–7] Some studies predict roll lifetime, but they are limited to more predictable wear, which involves small-scale surface damage.[8,9]

Laboratory tests confirmed that oxidation affects crack propagation and material removal, but only in small volumes.[10–12] Early spalling of larger particles is more detrimental. According to Colàs et al.,[11] oxidation loops are critical to understanding why high-chromium rolls experience early spalling. Laboratory oxidation experiments in a humid atmosphere,[2,3,12,13] tribological tests (disk-on-disk tests[14,15] or pin-on-disk tests[16–18]), and thermal fatigue tests[6,10,19] showed weak penetration of the oxide from the surface. These results do not explain the origin of the significant oxidation commonly seen in work rolls.[6] The test conditions in the aforementioned studies were not as harsh as the conditions that occur on the surfaces of work rolls during industrial rolling, hence the shallow oxide penetration.[20] The presence of water vapor increased oxidation in the laboratory experiments.[21,22]

Analyses of industrial defects and laboratory tests mimicking severe hot rolling conditions show that pro-

*Corresponding author's e-mail:
jaka.burja@imt.si (Jaka Burja)

nounced oxidation is a likely cause of early spalling.[2,6,7,23]

Laboratory tests simulating realistic hot rolling conditions are necessary to better explain the complex influence of loads, environmental conditions, and microstructure on the development of roll oxidation behavior. In this study, we present three distinct modes of early spalling of the material from the roll surface layer.

2 EXPERIMENTAL PART

A centrifugally cast roll shell made of high-chromium steel was used for the experiments; the chemical composition is given in **Table 1**. Samples were prepared by grinding and polishing to 1 μm. The samples were analysed with scanning electron microscopes (SEM) (JEOL 5610, 6450-F, ThermoFisher ScientificFEI NanoSEM, and Quattro S field-emission SEM, ZEISS CrossBeam 550) using secondary electron images (SEI) and backscatter electron images (BEI), as well as energy dispersive spectroscopy (EDS). The microstructure consisted of primary, eutectic, and secondary carbides, and a martensitic matrix, as presented in another paper.[24] The samples were tested on a Gleeble 1500D thermomechanical simulator. They were round and hollow to allow water cooling after the heating cycle. The samples were heated to the maximum test temperature in approximately 3 s, followed by water cooling and drying of the surface with compressed air; the temperatures were (500, 600 and 700) °C. Details of the test rig can be found in previous work.[19,25] Experiments simulated harsh oxidation and thermal conditions similar to those in industrial rolling. Special cases of severe surface degradation due to spalling of large particles were analysed to reveal distinct modes of early spalling.

Table 1: Chemical composition of high-Cr steel in *w*/%

C	Si	Mn	P	S	Cr	Ni	Mo	V
1.65	0.66	0.73	0.017	0.009	11.28	1.94	1.17	0.26

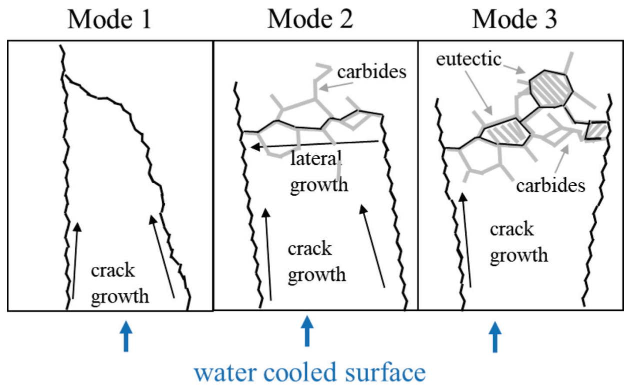

Figure 1: Three distinct modes of crack linking leading to early spallation, Mode 1 – direct linking, Mode 2 – linking with a lateral crack, Mode 3 – linking with oxidized eutectics[24]

3 RESULTS AND DISCUSSION

Oxidation-assisted cracking is prominent during thermal fatigue, where an increase in the volume of oxidized material causes additional stresses at the crack tip. Bombač et al.[6,19] show that cracks can grow even at lower thermal stresses with oxidation-assisted cracking, especially in the Cr-depleted zones along primary and eutectic carbides. This can be evidenced by the oxidation of the narrow bands adjacent to the carbides and eutectic carbides.[19]

Based on microstructural observations of thermally fatigued specimens, three modes of crack linking leading to early spalling of large particles have been identified and are described below, and schematically presented in **Figure 1**.[24]

Mode 1 – Direct linking of two radial cracks, where at least one of the cracks changes the growth direction.

Mode 2 – Linking of two radial cracks with lateral cracking between them.

Mode 3 – Linking of two radial cracks via oxidized eutectic areas in the lateral direction between radial cracks.

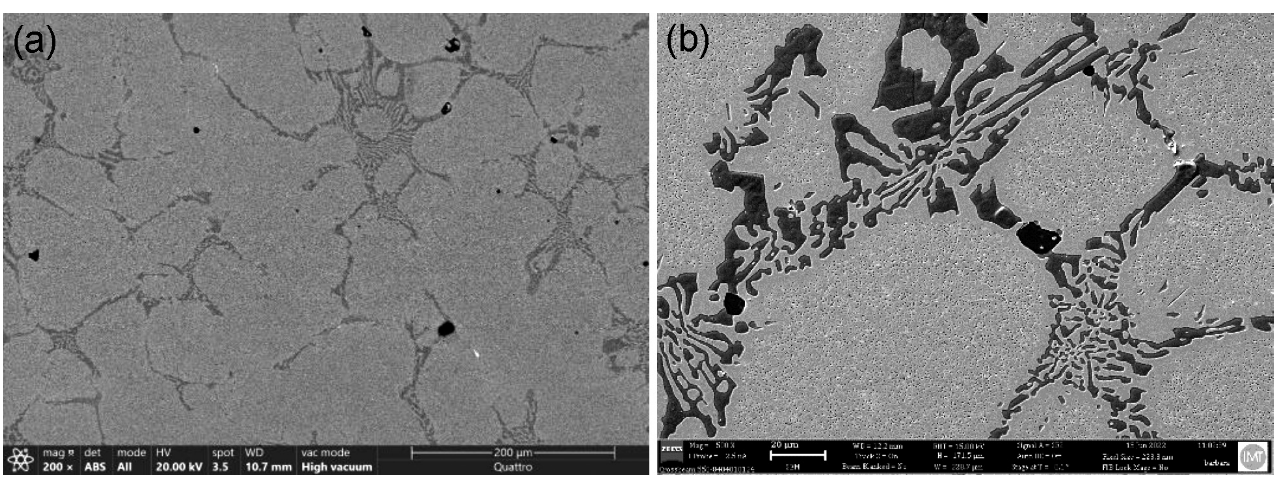

Figure 2: Carbide network in high-chromium steel: a) carbide network, SEM BEI; b) eutectic, SEM BEI

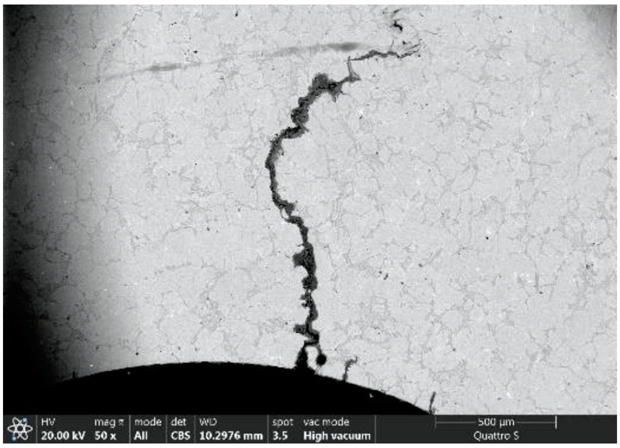

Figure 3: Single deep radial crack, found in a sample tested at 700 °C for 4500 cycles, SEM BEI

The carbide networks with eutectic areas in high-chromium steels, presented in **Figure 2**, are essential for the rapid crack growth. Carbides present a brittle phase and also deplete the chromium-rich matrix, making it more susceptible to oxidation.

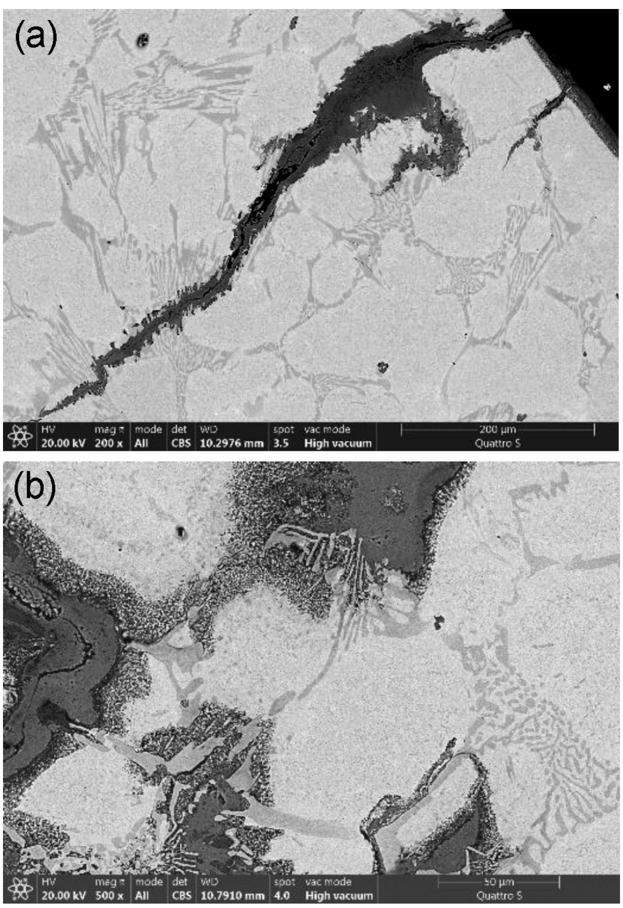

Figure 4: a) Radial crack with pronounced oxidation along carbides, SEM BEI; b) significant oxidation of the Cr-depleted matrix in the eutectic and along carbides, found in a sample tested at 700 °C for 4500 cycles, SEM BEI

Formation of deep cracks is especially prominent at higher testing temperatures (700 °C), with a radial crack depth of over 1 mm in as shown in **Figure 3**. When a crack reaches such depths, the tension caused by thermal stresses disappears, and is no longer the main driving force for the crack formation. However, single cracks do not cause critical surface damage. The surface is seriously damaged when cracks link, allowing for spallation of large particles.

During operation cracks are filled with oxidation products. Oxides have a significantly lower density and therefore take up more space, causing additional stress at the crack tip. The areas along the carbides are more susceptible to oxidation due to Cr-depletion (**Figure 4a**), and eutectic areas are especially susceptible to it (**Figure 4b**).

Early spalling of large particles can occur when two radial cracks link (Mode 1). These cracks originate from the cooled surface. Crack growth is accelerated in the radial direction due to a successive carbide arrangement. This is the simplest mechanism, and Cracking Mode 1 is shown in **Figure 5**.

The two radial cracks can grow along the carbide network. When one crack slightly changes the growth direction and starts to grow towards the other crack, the two cracks are eventually linked. This phenomenon causes a large particle to be detached from the surface, leading to eventual spalling. As shown in **Figure 5**, the particle size is approximately 1 mm in diameter, causing severe and irreparable surface degradation.

The spalled particle size is related to the initial axial distance between the cracks, inclination of the crack growth angle, and different depths of crack linking.

Linking between two radial cracks by a lateral crack can cause spalling of large particles (Mode 2). Again, oxidation-assisted cracking of the carbide network plays an important role, as it facilitates the formation of lateral cracks, as shown in **Figure 6**.

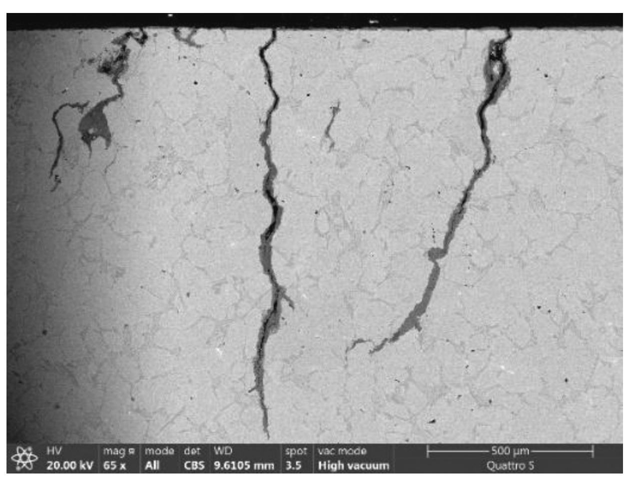

Figure 5: Accelerated crack growth in a successive arrangement of eutectic and primary carbides, in the radial direction at 700 °C after 200 thermal cycles, SEM BEI

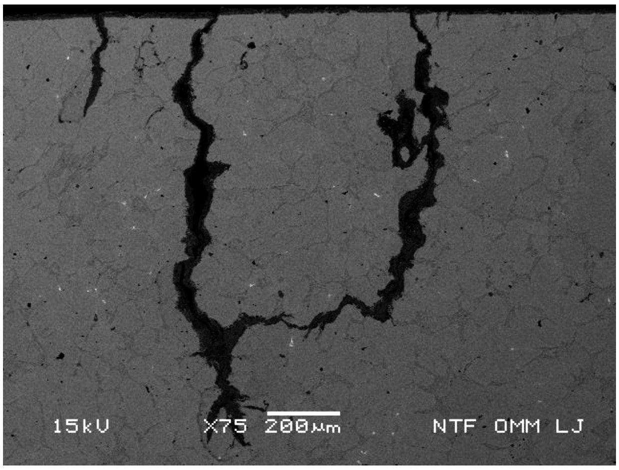

Figure 6: Lateral linking of two radial cracks at approximately 800 µm, observed in a sample tested at 700 °C after 2500 thermal cycles, SEM SEI

As shown in **Figure 6**, cracks mostly form along the carbide networks and are heavily oxidized. This leads to spallation of an approximately 0.5 mm wide and 1 mm long particle, causing catastrophic surface damage.

Spalling of a large particle can form as a result of oxidation of the eutectic between two radial cracks (Mode 3). Oxidation of eutectic areas was observed in a specimen thermally fatigued at 700 °C for 200 thermal cycles (**Figure 7**). Early oxidation of several separate small eutectic regions occurred. The eutectic areas were located between two radial cracks. The progress of oxidation eventually led to their linking. The depth of the oxidized regions is in a range of 100–200 µm with the radial cracks visible on both sides, roughly 300 µm apart (**Figure 7**).

The Mode 3 failure presented in **Figure 7** causes a particle over 0.5 mm wide to spall from the surface. Similarly to the previous cases, this will be a cause for a roll replacement.

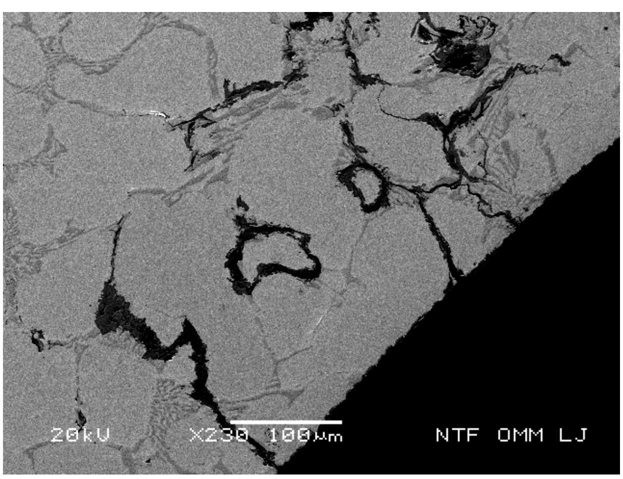

Figure 7: Accelerated crack growth in a successive arrangement of eutectic and primary carbides, crack growth in the radial direction, and linking via eutectic oxidation at 700 °C after 200 thermal cycles, SEM SEI

4 CONCLUSIONS

From the metallographic analysis presented in this work, the following conclusions can be drawn:

Three relevant modes of sample surface degradation are crucial for the early spalling of large particles.

Mode 1: direct linking of radial cracks.

Mode 2: linking of radial cracks via a lateral crack.

Mode 3: linking of radial cracks via oxidized eutectics.

Sufficiently high test temperatures with high thermal stresses, oxidation of eutectic carbides, oxidation in Cr-depleted bands along carbide networks, and an increase in the stresses around oxidized eutectics, as well as the arrangement of the carbide networks themselves significantly increase the danger of large particle spalling.

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