High-temperature abrasion resistance and wear mechanisms of chilled high-chromium cast irons

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Abstract. Hard and highly wear resistant chilled cast irons are of high interest in heavy industries like mining and steel production to achieve durable and sustainable wear protection. In this work a comprehensive view on abrasion mechanisms and the change in microstructure of these materials at elevated temperatures is targeted. Therefore, two different types of commercially available chilled high-chromium white cast irons were chosen. Detailed material characterization and hot hardness tests up to 1000°C were performed to get a first indication of temperature stability. For analysis of abrasive behaviour dry sand/steel wheel testing up to 700°C was conducted. A major part of the work was a thorough examination of the wear tracks and the influence on the microstructure. In the investigated materials chromium carbides Cr(Fe)\(_7\)C\(_3\) and Mo-rich precipitations are present; the size and stoichiometry depend on the chemical composition. According to the differences in carbide size and type and the respective matrix composition, the hardness and abrasive behaviour changes, especially at higher temperatures. Incorporation of SiC abrasive in the wear zone leads to an in-situ wear protection, which was especially effective at 300°C increasing material’s wear resistance compared to room temperature (RT). At higher temperatures up to 700°C it was possible to compensate the hardness loss of the cast iron materials.

1. Introduction

Many fields of heavy industry such as industrial mining and milling or the production of steel rely on applications with exceptional abrasion and wear resistance under elevated temperatures. High-chromium white cast irons are used in harsh abrasive environments as appear for mechanical components which somehow manipulate or process large quantities of raw and bulk materials [1,2]. For these highly abrasive applications mainly hypoeutectic alloys (<4.3 % C) with Cr-contents of up to 30 wt. % are commonly applied [3]. Their high volume fraction of hard eutectic chromium-rich carbides in the microstructure makes them extremely abrasion resistant and leads to beneficial mechanical properties such as its high hardness [4-6]. Additionally, the toughness of the matrix exhibits substantial influence on the wear behaviour [7]. The applied chilled casting method improves wear resistance through defined directions of solidifications and finer and more homogeneously distributed carbide grain structure [8,9].

The main objective of the presented work is the comprehensive determination of wear behaviour [10] of two high-chromium white cast irons with distinct differences in chromium content. Abrasion resistance of said materials was tested at elevated temperatures up to 700°C. Furthermore, the influence of applied harsh abrasive environment on the subjacent microstructure was thoroughly examined.
2. Experimental section

2.1. Materials investigated

In the present study, two hypoeutectic cast irons commonly applied in high temperature applications were compared. The chemical composition of the samples can be seen in Table 1. Both materials are of relatively common composition but significantly differ in the amount of added Cr, which is of fundamental importance for hardness and wear resistance through carbide precipitation. KALCAST 153 contains 16 wt. % Cr and is in the medium Cr-range for high-Cr white cast irons. In KALCAST 157, the amount of Cr is increased to 26 wt. %. All specimens were cut directly from as-produced chill casted plates and surface-ground for further processing in tribological tests. According to their difference in Cr-content the materials reached hardness values of ~760 HV10 (KALCAST 153) and ~840 HV10 (KALCAST 157).

Materials were analysed by scanning electron microscopy (SEM – JEOL JIB-4700 F) equipped with an energy-dispersive X-ray spectroscope (EDS - Bruker X-flash 6/30) and an electron backscatter diffraction detector (EBSD – Bruker e-Flash HR). Phase analysis was performed pre- and post-testing, aiming on microstructural changes, carbide breaking and particle embedment.

| Table 1: Chemical composition of applied cast iron samples. |
|---------------------|-----|-----|-----|
|                      | C  | Cr  | Mo | Fe |
| KALCAST 153          | 3  | 16  | 1  | 78 |
| KALCAST 157          | 3  | 26  | 1.5| 65 |

2.2. Materials investigated

Figure 1 depicts the images of examined cast irons microstructures. Both cast irons show fine martensitic matrix structure with precipitated carbides (dark areas). KALCAST 153 tends to form fewer primary carbides than KALCAST 157. Combined EDS and EBSD spot analyses point out that those carbides mainly are of (Cr, Fe)_xC_y-type, whereas the EBSD measurements indicate a mixture of both, τ-carbides (Cr,Cr,Fe)_xC_y and M_23C_6-type carbides, depending on local segregations within the carbides. Secondary carbides (small dark gray phases within the martensitic matrix) are of Cr_C3-type and can be detected in KALCAST 153, where their appearance is polygonal, whereas in KALCAST 157 both carbide types can be found in the matrix as spikes. Mo-rich precipitates can be easily visualized as bright grey areas – the amount of those precipitations correlate with the amount of Mo present; in KALCAST 153 fewer precipitates can be seen than in KALCAST 157.

2.3. Wear testing methods

To evaluate the materials’ abrasive wear behaviour three approaches were undertaken from RT to high temperatures: i) Low-stress abrasion testing according ASTM G65 procedure B (130 N normal load, 1436 m sliding distance, RT, according to the standard [11]), which gives a good indication of low-stress wear behaviour, e.g. loose material sliding over a chute.
ii) Usually, with increased temperatures the hardness of materials decreases, which gives a first indication on the abrasive wear resistance. Therefore, the hot hardness of the materials was measured up to 1000°C with a test device developed at AC²T [12]. Indents with a Vickers-diamond were made (HV10, 3 indents per temperature) from RT to 1000°C in steps of 100°C. To avoid surface deterioration by oxidation the test procedure was carried out in vacuum atmosphere. Measurement of the indents was done by means of optical microscopy after cooling of the samples. iii) Abrasive wear resistance at process temperature is of high importance in many industrial applications. Therefore, we made high-stress abrasive wear tests with a block-on-ring configuration, where abrasive is introduced into the wear gap [11]. For equal temperature conditions, both, the abrasive and the sample, are heated. Tests were done at RT, 300, 500, and 700°C with 10 N normal load. A martensitic steel wheel counter-body with 500 HV and broken SiC (size F36, 425-600 µm) at a flow rate of 150 g/min as abrasive were used, this entails much higher stress in the tribocontact, leading to high-stress conditions. The sliding speed was adjusted to 1 m/s and testing time was 10 min, resulting in 600 m sliding distance. The wear volume was calculated via weight loss and the indicated material density, normalized with the sliding distance resulting in the wear rate (mm³/m). Oxidation of the samples at elevated temperatures generally leads to an increase in sample weight, whereas herein this is negligible compared to the weight loss caused by the abrasion experiments [13]. Hence, the influence of oxidation on the sample weight was neglected for calculations of the wear rates.

3. Results and discussion

3.1. Hot hardness

Results of the hot hardness tests are shown in Figure 2. In the range from RT to ~500°C a significant difference in hardness can be observed: the cast iron containing more Cr-carbides (KALCAST 157) shows much higher hardness for this temperature-range. At 600°C the hardness of the high-Cr sample slightly changes to a similar level as for the lower-Cr cast iron. There, the influence of the softened matrix becomes predominant and the high amount of carbides cannot compensate the loss of mechanical resistance against the indentation. At high temperatures of >800°C, a higher hardness for the cast iron containing the higher Cr-amount can be measured, which can be attributed to the different appearance of the present carbides, since spike-like secondary carbides are present in the matrix at a higher amount.

3.2. Abrasion experiments

Results of the standard G65 experiments (see Figure 3) revealed substantial differences in wear resistance at low-stress conditions, which could mainly be caused by the difference in hardness and carbide content of the two materials. Containing low amounts of Cr, KALCAST 153 exhibited much higher wear rates as could be observed for KALCAST 157. The increased amount of hard Cr-carbides could resist the applied abrasive stress much more effectively. An increase of Cr content of 10 wt.% could reduce the wear losses by over 30 % for the herein
tested low-stress environment. This can be attributed to the increased amount of coarse primary carbides of KALCAST 157 compared to KALCAST 153. Furthermore, spike-like sub-micron sized secondary \(\tau\)-carbides of \((\text{Cr}_x\text{Fe}_y)_2\text{C}_6\) and \(\text{M}_7\text{C}_3\)-type carbides in KALCAST 157 tend to increase the low-stress abrasion resistance of the matrix at a higher level, compared to the polygonal \(\text{M}_7\text{C}_3\) secondary carbides within KALCAST 153.

For high-stress abrasion experiments (see Figure 4) at room-temperature a similar wear rate was observed for both cast irons – slightly higher for low-Cr cast iron, KALCAST 153. Interestingly, increasing the testing temperature to 300°C induced an extensive drop of wear losses for both materials, especially for KALCAST 153, resulting in a substantially higher wear resistance of this material compared to KALCAST 157. A further increase of temperature to 500°C lead to a raise in wear rates to the room temperature-level for KALCAST 157. Even for 700°C tests wear losses for this material remained at the same level and did not increase any further. From very low wear rates at 300°C, KALCAST 153 showed a linear increase when temperatures were raised to 500°C and 700°C. At 700°C both iron cast materials again showed similar wear rates, albeit results for the low-Cr KALCAST 153 were still slightly lower. Generally, wear rates of KALCAST 157 vary much less (~20%), compared to KALCAST 153 whereas in the medium range of 300-500°C KALCAST 153 exhibited substantially lower material losses (45%) compared to room temperature.

Cross-sectional SEM analyses of the high-stress abrasion wear tracks provide a deeper understanding of the occurring wear mechanisms [14,15]. Figure 5 shows SEM images of metallographic cross-sections of wear tracks at RT, 300°C and 700°C to depict the correlation of the microstructure to wear mechanisms at different temperatures. As seen in these images, wear mechanisms change with increasing temperature. At RT only few SiC-abrasive particles are incorporated since the initial matrix hardness is at a high level. Increasing the samples’ temperature, which decreases the matrix hardness, tends to have a positive effect on the in-situ formation of a tribolayer, more precisely a mechanically mixed layer (MML) like observed in previous studies [16,17].

![Figure 4: High-stress abrasion results.](image)

![Figure 5: Cross-sectional SEM analysis of the wear scars including inserts of overlayed EDS-mappings.](image)
At 300°C wear rates are the lowest, which may be attributed to a still sufficient hardness of the matrix against removal by abrasive material. But low enough to incorporate very hard SiC abrasives to form a MML, hindering further wear loss. At 500°C and 700°C KALCAST 153 exhibits increasing wear rates, which can be assigned to a lower matrix hardness. Leading to breaking of the coarse secondary carbides within the matrix, this impedes their effectiveness as wear protection. KALCAST 157 features finer secondary carbides in the matrix, reducing hardness loss and impeding primary carbide breakage, but also allowing for MML formation. In summary, both materials are capable of improving, their RT-wear resistance by in-situ MML-formation, which compensates for the hardness loss due to applied elevated temperatures.

4. Conclusions
High-temperature abrasion is a serious issue in many industrial applications. Within this work two white cast irons with high Cr-content (16 vs. 26 wt. %) were evaluated regarding their abrasive wear resistance and wear mechanisms up to 700°C. It was found, that the higher Cr-content led to the precipitation of larger primary carbides, but also to spike-like (Cr_{x}-Fe_{y})_{23}C_{6} and M_{2}C_{3}-type secondary precipitations, which were especially beneficial in low-stress abrasion at room temperature. The lower Cr alloy showed polyhedral M_{2}C_{3} secondary precipitations, which allowed more incorporation of abrasive in high temperature high-stress testing, improving its wear resistance up to 45% compared to room-temperature.

Acknowledgments
This present study was funded by the accompanying partner Kalenborn Kalprotect GmbH and the Austrian COMET Programme (K2-Project InTribology, no. 872176) and carried out at the “Excellence Centre of Tribology”, Wiener Neustadt, Austria (AC2T research GmbH).

References
[1] Ngqase M and Pan X 2020 J. Phys. Conf. Ser. 1495 (1), p. 012023. IOP Publishing
[2] Kvon S S, Kulikov V Y, Filippova T S and Omarova A E 2016 Metalurgija 55(2) 206-08
[3] Laird G, Gundlach R and Röhrig K 2000 Abrasion-resistant cast iron handbook (Illinois: American Foundry Society) p. 72
[4] Kopyciński D, Kawalec M, Szczesny A, Gilewski R and Piasny S 2013 Arch. Metall. Mater. 58
[5] Pero-Sanz J A, Plaza D, Verdera J I and Asensio J 1999 Mater. Charact. 43(1), 33-39
[6] Lu B, Luo J and Chioveli S 2006 Metall. Mater. Trans. A 37(10), 3029-38
[7] Hussain N, Kumar A and Vijayanand P 2014 Int. J. Eng. Res. Technol. 3(7), 2278-81
[8] Bedolla-Jacuinde A, Arias L and Hernández B 2003 J. Mater. Eng. Perform. 12(4), 371-82
[9] Smith M 1994 The influence of the degree of transformation of M7C3 carbides to M23C6 carbides on the properties of high chromium white cast irons (Doctoral dissertation, University of the Witwatersrand, ZA)
[10] Widder L, Grafl A, Lebel A, Tomastik C and Brenner J 2011 Tribol. und Schmierungstechnik, 58(2), 11-15
[11] ASTM International 2010 ASTM G65-04-Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus
[12] Varga M, Flasch M and Badisch E 2017 Proc. Inst. Mech. Eng. J 231(4), 469-78
[13] Liu H N, Nomura M, Ogi K and Sakamoto M 2001 Wear 250(1-12), 71-75
[14] Rojacz H, Mozdzen G, Weigel F and Varga M 2016 Mater Charact. 118 370-81
[15] Rojacz H, Premauer M and Varga M 2018 Wear 410 173-80
[16] Varga M and Badisch E 2017 Wear 384-385 114-23
[17] Rojacz H, Pahr H, Baumgartner S and Varga M 2017 Trib. Int. 113 487-99