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The role of microstructure in high stress abrasion of white cast irons

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A B S T R A C T

The abrasion wear resistance of white cast irons can be controlled primarily by adjusting the size, size distribution, and volume fraction of the carbide phase. The main physical property of white cast irons correlating with abrasion resistance is hardness. This study concentrates on the evaluation of hardened and stress relieved, normalized, self-hardened, and as-cast states of high chromium white cast irons in high stress abrasion. The correct size and orientation of the carbides were found to be crucial for the wear resistance of white cast irons in high stress abrasive conditions. The different annealing procedures affected the formation of the carbide structure and its distribution, as well as the microstructure of the matrix. The austenite-to-martensite ratio together with a beneficial carbide structure was found to have a strong effect on the abrasion wear resistance of WCI specimens.

1. Introduction

White cast irons (WCI) are considered one of the earliest wear resistant materials. Despite the long history of white cast irons, they are of continuing interest due to the wide variety of different compositional features combined with a relatively low production cost. The effects of different fractions of the carbide phase and the microstructures of the matrix on abrasive wear have been extensively studied [1–5].

The abrasion wear resistance of white cast irons can be altered by adjusting the carbide phase properties. The relative hardness and toughness of the matrix phase also play an important role in the abrasion wear resistance [6]. For optimal abrasion resistance, the microstructure and hardness of the white cast irons must be appropriate for the application. The required properties are obtained by careful control of the material composition and the processing route.

The carbide orientation has been found to be one of the main features affecting the abrasive wear performance of white cast irons [7,8]. Hawk et al. [9] found that when the carbides were oriented with their long axis perpendicular to the wear surface, the abrasion resistance was considerably reduced. The best wear performance was achieved when the long axis of the carbides was parallel to the wear surface and perpendicular to the wear (load) direction. According to Coronado et al. [10], however, at lower loads the mass loss was independent of the orientation of the carbides with respect to the wear direction, and only at higher loads the carbide orientation perpendicular to the direction of wear led to better abrasive wear performance.

Steel and WC-Co specimens have been studied earlier with the same test method as used in the present study [11], and the results show that the wear rate of these materials is hugely affected by the abrasive properties. Granite with quite a high compressive strength would probably lead more to the cracking of carbides, while quartz with a much lower compressive strength would most likely lead more to the removal of the matrix phase and pull-out of carbides. Despite the large number of papers published on the abrasion wear resistance of white cast irons, the wear performance of WCI's in different annealing conditions has not been much studied nor reported. This study concentrates on the effects of different heat treatments on the high stress abrasion behavior of high chromium white cast irons. The four studied conditions are hardened and stress relieved, normalized, self-hardened, and as-cast.

2. Materials and methods

High chromium white cast irons of similar composition were tested in high stress abrasion in hardened and stress-relieved (H), normalized (N), self-hardened (ACSH), and as-cast states (AC). The studied high chromium abrasion resistant cast irons belong to the highest chromium content group EN-GJN-HB555(XCr23) of EN-12513 with 23 wt.% $<$ Cr $\le$ 30 wt.%. They typically have a microstructure consisting of complex carbides in a matrix which, in the hardened condition, is predominantly martensitic but can also contain some austenite or other transformation products of austenite.

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Table 1
Nominal compositions (wt%) of the studied castings.

Casting	C %	Si%	Mn%	P %	S %	Cr %	Ni %	Mo%	Cu %	Al %	N %	V %
WCI 1	2.9	0.82	0.8	0.028	0.018	28.2	0.62	0.15	0.08	0.002	0.094	0.056
WCI 2	2.94	0.94	0.7	0.028	0.027	27.1	0.71	0.61	0.58	0.002	0.12	0.049

2.1. Materials

The nominal compositions of the alloys are presented in Table 1. Casting WCI 2 had a higher amount of copper (Cu) and molybdenum (Mo).

Hardening of the casting involves slow heating up to a pre-defined temperature range (in this work 900 ˚C to 1050 ˚C), holding there for a time appropriate for its thickness and chemical composition, and rapid cooling. Only simple shaped castings can be oil quenched without the risk of cracking, and therefore rapid cooling is most frequently done using air/gas cooling. The air/gas cooling can be carried out by fan cooling, forced gas, or atomized liquid spray techniques. It can be necessary to cool complex shaped castings in still air. In such circumstances it is important that the material's chemical composition makes provision for sufficient hardenability. Stress relieving consists of slow heating up to the temperature range of 400 ˚C to 500 ˚C, holding for a sufficient time and slowly cooling down with the furnace to about 200 ˚C. Normalizing consists of heating as in hardening, but with slow cooling down to RT with the furnace.

The cooling rate will determine the resulting microstructure and hardness of the high chromium abrasion resistant cast irons. In this study, the cooling rate was varied according to the different casting wall thickness. Table 2 summarizes the studied white cast irons, their heat treatment states, and the measured hardness values.

2.2. Materials properties

Bulk hardness values were measured with Struers Duramin A-300 hardness tester and the micro hardness values with a SEM-integrated micro hardness tester Anton Paar. Structural analyses were done with Panalytical Empyrean Multipurpose Diffractometer (XRD) and are presented in Fig. 1.

Fig. 2 presents the microstructures of the studied materials below the wear surface, characterized with the Philips XL30 scanning electron microscope (SEM). AC, N and ACSH have an oriented structure with long carbides, whereas the H specimen has a non-uniform structure with different shapes of carbides. The densest carbide structure was found in the ACSH specimen. The longest mean free path was observed in the microstructure of the N specimen.

2.3. Crushing pin-on-disc test

High stress abrasion tests were conducted with the crushing pin-on-disc device. It is based on the common pin-on-disc principle with the addition of loose abrasive particles and a cyclic crushing stage [11]. All the specimens were subjected to a pre-wear period of 15 minutes with 2–4 mm size of abrasive. During this stage the wear surface achieves the steady state of wear. The actual wear test was 30 minutes long with 2–10 mm granite abrasive (from Sorila quarry in Finland), and the results are presented as the median values of three tests. One test includes 20 minutes of crushing action and 10 minutes of idle time with the specimen pin being lifted above the gravel bed. The hardness of the Sorila granite was ca. 800HV, and the rock consisted of the following minerals in the order of decreasing volume fraction; plagioclase, quartz, orthoclase, biotite and amphibole. The selected granite is a very hard and abrasive mineral with high compressive strength.

Table 2
Heat treatments and hardness values of the tested white cast irons.

Heat treatment state	as-cast, slow cooling rate	as-cast, fast cooling rate	hardened and stress relieved	normalized
Specimen code	AC	AC SH	H	N
Casting	WCI 1	WCI 2	WCI 2	WCI 2
Bulk Hardness (HV10)	351	702	740	718
Matrix hardness (HV0.1)	320	597	702	740
Carbide hardness (HV0.1)	~1700	~1700	~1700	~1700

Fig. 3 presents the construction of the test device. The pin (WCI specimen) had a diameter of 36 mm and height of 35 mm. The disc (160 mm in diameter) used in these tests was made of structural steel (200 HV5). The disc rotates at 28 RPM, and the pin is cyclically pressed with a 240 N force towards the disc. The disc and the pin never make a direct contact with each other due to the layer of abrasives being crushed between them. The crushing cycle consist of two phases. The pin crushes abrasives for two rotations (5 s), after which the pin is lifted up for one rotation (2.5 s) and then pressed again down to the pile of abrasives for a new cycle. This cycle ensures that there is always a sufficient amount of abrasives between the pin and the disc. The wear surfaces and cross-sections were characterized using SEM. Wear surfaces were also characterized with optical profilometer Alicona InfiniteFocus G5 3D.

3. Results and discussion

WCI specimens in each of the four annealing conditions were tested with the crushing pin-on-disc. Each specimen was tested three times. Fig. 4 presents the results as median mass loss together with the bulk hardness values. The results were scaled to the wear area of 1000 mm^2 in order to obtain as reliable and comparable results as possible. The highest mass loss was measured for the AC specimen, as could be expected from its low hardness. The H and ACSH specimens were at quite the same level of mass loss. The scatter in the results of H specimens was very low. However, it is worth mentioning that the wear rate of the ACSH specimen decreased after each 30 minutes of testing, which explains the slightly increased standard deviation of the test runs on this specimen. Actually, the lowest wear rate was observed in the last test run of the ACSH specimen. Due to the fact that the median values were used to present the overall wear of the specimens, it seems that the H specimen reached the lowest values. The N specimen had a higher wear rate than specimen H with quite similar matrix hardness.

The surface of the lowest hardness specimen AC had deformed most during the wear test. Deep and wide scratches were present, and the wear surface appeared to contain quite few abrasive residues due to the constant material removal. The low hardness matrix had not been able to withstand the contact pressure caused by the abrasive particles sliding on the surface, and thus the carbides were crushed. The crushed carbides had also been participating in the actual wear process together with the granite abrasives. Fig. 5 presents micrographs from the typical wear process of the AC specimen: it is obvious that the matrix has deformed below the wear surface, which has caused crushing of the carbides even deeper inside the material, down to 50 µm below the surface. When these long, crushed carbides have opened to the wear surface, the crushed carbide material has been removed by the deformation movement of the matrix and the carbides have been