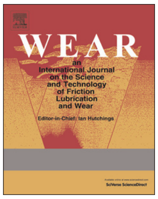
Wear 338-339 (2015) 27–35

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear



Influence of temperature on abrasive wear of boron steel and hot forming tool steels

S. Hernandez [a,*], J. Hardell [a], H. Winkelmann [b], M. Rodriguez Ripoll [b], B. Prakash [a]

[a] *Division of Machine Elements, Luleå University of Technology, Luleå SE-97187, Sweden*
[b] *AC^{2}T research GmbH, Viktor-Kaplan-Straße 2, 2700 Wiener Neustadt, Austria*

ARTICLE INFO

Article history:
Received 28 April 2014
Received in revised form
18 March 2015
Accepted 15 May 2015
Available online 22 May 2015

Keywords:
Hot hardness
Elevated temperatures
Boron steel
Tool steel
Abrasive wear

ABSTRACT

In many industrial applications the occurrence of abrasive wear results in failure and replacement of components. Examples of these applications are found in mining, mineral handling, agriculture, forestry, process and metalworking industry. Some of these applications also involve operation of relatively moving surfaces at elevated temperatures which increases the severity of wear. A typical example of high temperature wear phenomena is that of tool steels during interaction with boron steel in hot forming. Some studies have been carried out regarding the high temperature tribological behaviour of these materials but results pertaining to their high temperature three body abrasive behaviour have not been published in the open literature. In this work, the high-temperature three body abrasive wear behaviour of boron steel and two different prehardened tool steels (Toolox^{33} and Toolox^{44}) was investigated using a high temperature continuous abrasion machine (HT-CAT) at different temperatures ranging from 20 °C to 800 °C using a load of 45 N and a sliding speed of 1 ms^{-1}. The wear results were correlated to the hot hardness of the different materials measured by means of a hot hardness tester (HHT) at a load of 10 kgf. Scanning electron microscopy and energy dispersive spectroscopy (SEM/EDS) techniques were used to characterise the worn surfaces. The hot hardness measurements of the three different materials showed a slight but continuous decrease of hardness from room temperature to 600 °C. At temperatures above 600 °C the hardness showed a sharp decrease. The wear rate of Toolox^{44} was constant from 20 °C to 400 °C. On the other hand, Toolox^{33} and boron steel, showed a reduced wear rate from 20 °C to 400 °C attributed to an increased toughness and the formation of wear-protective tribolayers respectively. At higher temperatures (from 400 °C to 800 °C), the wear rate for these materials increased mainly due to a decrease in hardness and the occurrence of recrystallization processes.

1. Introduction

Abrasive wear constitutes about 50% of the total wear occurring in industrial applications [1]. Examples of these include mining and mineral handling, agriculture, forestry and process industry. The harsh conditions that are found in these applications can be further exacerbated at elevated temperatures which may lead to an increase in severity and higher wear rates.

Despite its significance in abrasive wear situations, the effect of temperature on three body abrasive wear has not received adequate attention. Some studies have been reported in the open literature where, e.g., the influence of temperature in a three body abrasive environment of copper and aluminium over a temperature range from ambient to 400 °C was studied by Soemantri et al. [2]. An increase in temperature showed a decrease in the wear rate of aluminium and an increase in the case of copper. They attributed this behaviour to the occurrence of an oxide scale that was easily removed in the case of copper and to the embedding of abrasive particles in the specimen surface in the case of aluminium. Fischer [3] investigated the wear mechanisms on different metallic materials at temperatures between 25 and 750 °C. It was observed that for temperatures up to 650 °C the wear rates decreased with increasing temperature due to the formation of thick surface tribolayers as a result of the mechanical interactions between the abrasive particles and the surface of the tested materials. Above this temperature, the grooves caused by abrasive particles were deeper than the thickness of these layers resulting in increased wear rates. Wu et al. [4] focused on the interaction of oxidation and abrasion on the wear of materials in a high temperature three body abrasive wear environment. They managed to distinguish between the respective effects of abrasion and oxidation on the volume loss of the specimens. Venkatesan et al. [5] studied the high temperature three body abrasive behaviour of medium carbon low-alloyed steel with different surface treatments. They found that for relatively low temperatures (room temperature

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[*] Corresponding author.
E-mail address: sinuhe.hernandez@ltu.se (S. Hernandez).

http://dx.doi.org/10.1016/j.wear.2015.05.010
0043-1648/© 2015 Published by Elsevier B.V.

to 300 °C) the wear resistance depended on the strength and ductility of the modified surface. At 600 °C, however, oxidation resistance and hot hardness had a greater effect on the measured wear rate. The effect of tribolayers on the wear behaviour in three body abrasion has been studied by several authors. During the interaction of sliding surfaces, the structure, mechanical properties, chemical composition and tribological behaviour of the surface layer become different from those of the bulk materials. Depending on the sliding conditions, these layers can be formed by agglomerated debris particles coming from one or both materials in contact. The newly formed layers are generally known as tribolayers [6].

Varga et al. [7] studied the wear reducing effects of the formation of different tribolayers under abrasive wear conditions at elevated temperatures. They concluded that the formation of tribolayers at high temperatures, their thickness and appearance depended on the microstructure and more importantly on the dispersion, size and structure of the hard phases of the materials investigated. Similarly, other authors have found the presence of tribolayers to be beneficial in terms of wear resistance, especially at elevated temperatures [8–12].

Boron steel has been used in harsh abrasive environments for a long time. Boron steels are also used at elevated temperatures in applications where a high abrasive wear resistance is required such as mining and materials processing. It is also employed as a workpiece material in hot stamping of structural and safety components for the automotive industry. Prehardened tool steels such as Toolox^{44} and Toolox^{33} are often chosen for applications such as plastic moulds or forming tools. In hot stamping process, tool steel and boron steel interact at elevated temperatures and recent studies carried out by Pelcastre et al. [13] and Boher et al. [14] have pointed out abrasive wear as one of the main wear mechanisms present in this process.

Although some studies have been carried out regarding the high temperature tribological behaviour of these materials, yet the studies pertaining to their high temperature three body abrasive wear behaviour have not been reported in the literature. In view of this, the objective of this paper is to investigate the effect of temperature on the three body abrasive wear behaviour of prehardened tool steels and boron steel.

2. Experimental work

2.1. Test materials and specimens

In this work, commercially available low-alloyed tool steels, Toolox^{44} and Toolox^{33}, and 22MnB5 boron steel were studied. The nominal composition and average room temperature hardness of the materials are given in Table 1. The influence of temperature on the impact toughness of the tool steels is presented in Table 2.

High temperature hardness was measured on rectangular specimens ($22 \times 50 \times 6$ mm^3). The surface of the samples was fine-polished with 0.25 μm silica particles up to a final roughness value (R_a) of 40 nm. For the high temperature continuous abrasion test, the sample dimensions were $25 \times 65 \times 7$ mm^3. In this case, the surfaces were ground with #120 grit SiC paper to a final roughness value (R_a) of 0.3 μm.

2.2. Test equipment and procedure

The hot hardness of test specimens was measured by using a specially developed Hot Hardness Tester (HHT) which is an extension of the Vickers HV10 test method (Fig. 1(a)). A load of 10 kgf is applied during 15 s in order to measure the bulk hardness. The tests are performed under low vacuum conditions (5 mbar) to minimize oxidation of the sample and diamond indenter. The heating is performed by means of a short wave (infrared) halogen emitter located below the test sample. The heating element is computer controlled using a type K thermocouple as feedback with an accuracy of ±5 °C. Before indenting the test specimen surface, the temperature is raised to the desired value and stabilised in order to minimize the measurement error. A pneumatic actuator relocates the sample under the indenter between each indentation. Five indentations were made at each temperature in order to have statistically representative results. The total test duration was 30 min.

The diagonals of the indentation marks were measured by means of optical microscopy after allowing the sample to cool down (ex-situ) and the Vickers hardness was calculated. The influence of thermal expansion at the selected testing temperatures is lower than 3% [7]. Hence, it is in the range of the test accuracy of the Vickers standard method and its effect is negligible. In the present work, the hot hardness was measured from room temperature (RT) up to 800 °C in increments of 100 °C.

The tribological tests were carried out by means of a High Temperature Continuous Abrasion Tester (HT-CAT) (Fig. 1(b)) [16]. The test rig is similar to the dry-sand wheel test described in the ASTM-G65 standard [17]. The test parameters were chosen to produce a well-defined wear track and measurable weight loss. Each specimen was cleaned in an ultra-sonic cleaner, thereafter rinsed with ethanol and finally dried in air before and after each test. The samples were heated through induction to the desired temperature and then loaded with 45 N against a rotating steel wheel with an abrasive flow in between, which resulted in high stress three body abrasion. The temperature was controlled by a type K thermocouple placed in a drilled hole near the surface of the test specimen. The steel wheel was made out of Hardox 500 (nominal hardness of ~530 HV) with a diameter of 232 mm.

The abrasive material employed was standard AFS 50-70 Ottawa silica sand with a nominal hardness of ~750 HV and a grain size of 212–300 μm (Fig. 2). A particle flow rate of 180 g/min

Table 2
Influence of temperature on impact toughness of Toolox^{44} and Toolox^{33} [15].

Material	Impact toughness [J]			
	20 °C	200 °C	300 °C	400 °C
Toolox^{44}	30	60	80	80
Toolox^{33}	100	170	180	180

Table 1
Chemical composition and hardness values of the experimental materials, Fe makes up the balance.

Material	Chemical composition (wt%)										HV$_{10\ kg}$
	C	Si	Mn	P	S	Cr	B	Mo	V	Ni	
Boron steel	0.2–0.25	0.2–0.35	1–1.3	Max 0.03	Max 0.01	0.14–0.26	0.005	–	–	–	190
Toolox^{44}	0.31	0.6–1.1	0.9	Max 0.010	Max 0.004	1.35	–	0.8	0.14	0.7	440
Toolox^{33}	0.22–0.24	0.6–1.1	0.8	Max 0.010	Max 0.004	1–1.2	–	0.3	0.1	Max 1	309