Tribology International 98 (2016) 155–171

Contents lists available at ScienceDirect

Tribology International

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

The influence of temperature on friction and wear of unlubricated steel/steel contacts in different gaseous atmospheres

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ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form
11 February 2016
Accepted 16 February 2016
Available online 24 February 2016

Keywords:
Steel
Gas atmosphere
Temperature
Friction and wear

ABSTRACT

The influence of temperature on friction and wear of unlubricated DIN 100Cr6 steel/steel contacts was studied in different anaerobic gaseous atmospheres, namely argon (Ar), nitrogen (N_2) and carbon dioxide (CO_2), and air atmosphere was used as benchmark. Tribological experiments were performed at high temperature (200 °C) and the results were compared with previously published results from experiments performed at ambient temperature (20 °C). Reciprocating ball-on-disc tribological tests were conducted with high contact pressures (maximum initial contact pressure of 1.5 GPa).

In all anaerobic gas atmospheres at high temperature, lower friction and wear were measured than in air atmosphere. The lowest friction and wear were measured in CO_2 atmosphere; they were slightly higher in N_2 atmosphere and even more slightly higher in Ar atmosphere. In all anaerobic atmospheres, different oxidation kinetics of steel surfaces occurred as compared with air atmosphere. For N_2 and CO_2 atmospheres, XPS analyses of the wear debris showed an increased concentration of non-carbidic carbon and furthermore for the CO_2 atmosphere, iron–carbon–oxygen layers were also found which probably provided the very favourable friction and wear properties observed in this atmosphere. In N_2 and CO_2 atmospheres, higher wear and friction were observed at high temperature than at ambient temperature, which indicates that at high temperature, a deterioration of the beneficial properties of the N_2 and CO_2-reacted tribolayers occurred. On the contrary, in Ar atmosphere at high temperature, a decreased adhesion and a significantly lower wear as compared with ambient temperature was observed.

1. Introduction

The effects of gaseous atmospheres on tribological properties of various metal contacts were extensively studied in second half of the last century as possible means for friction and wear reduction at extreme temperature and/or starved lubrication conditions [1–7], while there have been significantly less studies conducted over the last 15 years due to the emergence of advanced surface technologies (PVD coatings, etc.) that have helped to overcome the disadvantages of lubricating oils at these conditions. However, due to the increased use of gases in different mechanical applications, the influences of gaseous atmospheres on tribological behaviour of ferrous engineering materials such as steel and grey cast iron, just to name a few, has started to gain attention again. As examples are air conditioning and refrigeration compressors using environmentally friendly refrigerant gases such as CO_2 [8–11], which due to the increasingly strict environmental legislations and the need to reduce the global warming potential (GWP) index [12] are becoming increasingly important not only for the household industry but also for the automotive industry; the first vehicle models with CO_2 air conditioning systems will be available on the market in 2017 [13]. As the trend of lubricant-less and lubricant-free applications is becoming increasingly important in various engineering areas, and because direct contacts between surface asperities can occur under repetitious starts and stops or system overloads, understanding of the influence of gases on the properties of tribocontacts without the presence of lubricants is crucial for their optimisation and development.

Gas atmosphere may significantly affect the tribological behaviour of metallic materials. Namely, when exposed to a gaseous atmosphere, the highly reactive nascent metallic surfaces immediately interact with the surrounding gaseous molecules in order to form a thin passive surface film. This is observed in oxygen-containing atmospheres such as air: metallic oxide films are

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http://dx.doi.org/10.1016/j.triboint.2016.02.022
0301-679X/

formed on the metallic surfaces which decrease their adhesion and provide – in contrast to pure, non-oxidised metal surfaces, where very high adhesion may occur – relatively favourable friction and wear properties [2,5,6,14,15]. These surface layers may however differ significantly, depending on the chemistry of the gaseous atmosphere. In our previous study [16], unlubricated DIN 100Cr6 steel contacts were tested in different gas atmospheres at ambient temperature and very high contact pressure (maximum initial Hertzian contact pressure of 1.5 GPa, which lies above the material yield strength of about 1.1 GPa) and an outstanding decrease of friction and wear was measured in N_2 and CO_2 atmospheres as compared with air atmosphere, which was attributed to the formation of low-friction and/or low-wear tribolayers in these atmospheres. On the contrary, in Ar atmosphere friction and wear were markedly higher than in air, which was attributed to the absence of reactive gaseous molecules in the tribocontact.

Temperature may also have a significant effect on friction and wear of metallic contacts in gaseous atmospheres, since it affects the interactions between the gaseous molecules and the solid surface and thus determines the kinetics of the tribofilm formation and its chemistry. Namely, with increasing temperature, physical adsorption of gases to solid surfaces decreases, while chemical interaction increases [17]. At the same time, temperature increases the reaction rate since the number of colliding particles having the necessary activation energy increases, thus resulting in a higher number of successful collisions (when bonds are formed between reactants) – which is described by the Arrhenius equation [18]. However, while the effects of the gas pressure on friction and wear of metallic contacts were studied quite extensively [4,7,19–22], studies on the influence of temperature on friction and wear of metallic contacts in gaseous atmospheres are relatively scarce.

For AISI 52100 (DIN 100Cr6 equivalent) steel contacts in air, N_2 and Ar atmospheres, friction decreased with increasing temperature (up to 538 °C) while wear increased [3]. Under fretting conditions friction and wear of steel/steel (AISI 301/AISI 52100) contacts decreased with an increase of temperature up to 400 °C in air and Ar atmospheres; but increased at a higher temperature, 550 °C [23]. In that study, no significant effect of Ar atmosphere (containing 0.5% of O_2) on friction and wear was observed in comparison with air. In another study in Ar or N_2 atmospheres at ambient temperature, fretting wear of titanium, Ni–Cr–Al alloys and high temperature gas turbine alloys (MAR M-246, Haynes-188 and A-286) was lower than in air, while friction was slightly higher, but on the other hand, at elevated temperatures, higher friction and wear were reported for Ar and N_2 atmospheres as compared with air [24]. It was reported elsewhere that in air atmosphere, fretting wear of high strength alloy steel was strongly influenced by temperature and a significant reduction in wear was found between 24 °C and 85 °C [25]. The reduction in wear was due to the retention of wear debris within the wear scar, leading to the formation of a stable-load bearing bed and eventually a "glaze-layer" – these results support the view that this is due to a tribo-sintering process as described in [26]. Similar behaviour was reported also for reciprocating sliding contacts under mild sliding conditions (low loads and sliding speeds) [27–29], indicating that this mechanism is not only specific to fretting conditions.

This study focuses on the analysis of effects of different technical gases on friction and wear of steel contacts under severe operating conditions which usually occur in compressors (particularly in those with swash-plate geometry) due to the breakage of the lubricating film (non-lubricated sliding under high contact pressure and high temperature). The influence of air, CO_2, N_2 and Ar gas atmospheres on tribological and tribochemical behaviours of non-lubricated DIN 100Cr6 (AISI 52100 equivalent) bearing steel contacts was analysed under atmospheric gas pressure at 200 °C, which is typically the highest operating temperature that occurs in compressors. For comparison purposes, results from previously published experiments performed at ambient temperature (20 °C) are also presented [16].

2. Experimental

Measurements of friction and wear were conducted on an oscillating tribometer (SRV4, Optimol Instruments Prüftechnik GmbH, Germany), which was modified for the control of the surrounding gaseous atmosphere. A rubber sleeve with a thickness of less than 1 mm, diameter of ca. 60 mm and a height of ca. 40 mm was used as a gas chamber. It was mounted around the steel specimens and was sealed at the upper and the lower specimen holders to ensure gas tightness; in the lower specimen holder, inflow and outflow openings were designed for gas distribution, as shown in Fig. 1. In order to assure a constant gaseous atmosphere, a constant gas flow was established at a constant gas pressure. The gas flow and the gas pressure were controlled with a gas controller (Red-y smart pressure controller GSP, Vögtlin Instruments AG, Switzerland) at the inflow side and the O_2 concentration was controlled by using an O_2 sensor (O2 × 1 Transmitter, GE Sensing & Inspection Technologies GmbH, Germany) at the outflow side.

Air, Ar, N_2 and CO_2 gases were used as atmospheres in tribological tests. All anaerobic gases were supplied from gas cylinders (20 l for Ar and N_2 and 27 l for CO_2) and air was supplied from an oil-free air compressor (LF SS-10, Atlas Copco GmbH, Austria) and was dried with a high efficiency air dryer (PNEUDRI MIDIplus, Parker dominick hunter, Parker Hannifin Ltd., UK) before entering the gas chamber. The purities of the anaerobic gases, i.e. Ar, N_2 and CO_2, were higher or equal to 99.99%, 99.8% and 99.7%, respectively,

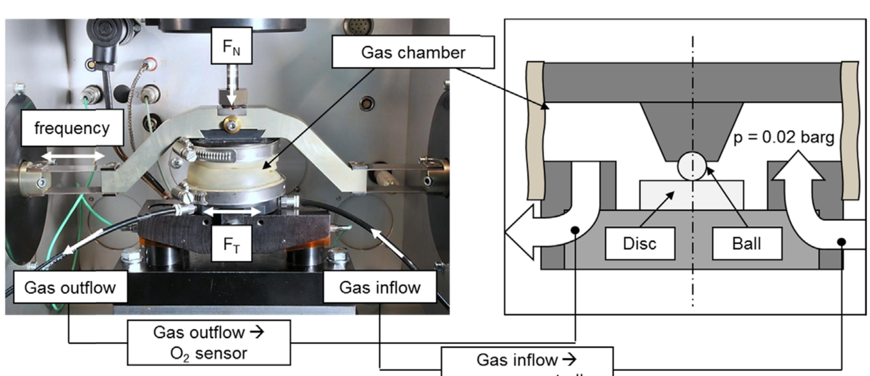

Fig. 1. Tribological test setup and a schematic representation of the gas chamber.