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Comparative scuffing performance and chemical analysis of metallic surfaces for air-conditioning compressors in the presence of environmentally friendly CO_2 refrigerant

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ABSTRACT

Carbon dioxide (CO_2) has received significant interest as an alternative refrigerant for air-conditioning compressors due to its environmental benefits. These environmental benefits include zero ozone depletion potential and minimal global warming potential compared to commonly used hydrochlorofluorocarbon and hydrofluorocarbon refrigerants. This study presents results for three typical metallic tribopairs commonly found in air conditioning compressors, namely, Al390-T6, gray cast iron, and Mn–Si brass against 52,100 steel pins. The experiments were performed using a specialized tribometer capable of simulating compressor conditions, and in the presence of CO_2 and polyalkylene glycol lubricant. It was found that the scuffing resistance of gray cast iron and Mn–Si brass was similar and both materials performed better than Al390-T6. Through scanning electron microscopy and energy dispersive spectroscopy it was found that lead in Mn–Si brass melted during scuffing, and prevented sudden catastrophic failure of Mn–Si brass, unlike gray cast iron and Al390-T6 which failed abruptly. X-ray photoelectron spectroscopy conducted on the worn surfaces showed that chemically different species were present on the surfaces and their lubricious effect, originating from different metal oxides, could explain the scuffing behavior of the investigated alloys.

1. Introduction

Since the early 2000s the air-conditioning industry has been focusing on alternative refrigerants for the replacement of hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants due to environmental regulations. The interest for long term solutions has been towards natural environmentally friendly refrigerants. Among different natural refrigerants such as water, air, isobutene (R600a), and ammonia, CO_2 (R744) is an attractive candidate [1]. CO_2 has been proven to be nontoxic and nonflammable with zero ozone depletion potential and negligible global warming potential compared to HCFC and HFC refrigerants [2]. However, its implementation in air-conditioning systems has been difficult because CO_2 systems have to be operated at high system pressures [3].

In air-conditioning compressors the solubility between refrigerant and lubricant plays an important role as the mixture circulates throughout the system and returns back into the compressor. Circulation has to be ensured to lubricate the tribopairs in the compressor and avoid pressure drops inside the system [4]. Materials such as Al390-T6, gray cast iron, and Mn–Si brass (UNS C67300) are commonly used for critical tribopairs in air-conditioning compressors, with Al390-T6 and Mn–Si brass found in automotive air-conditioning compressors and gray cast iron in industrial scroll compressors.

The wear and scuffing performance of silicon enriched aluminum alloys, such as Al390-T6, have been investigated before [5–8] with the main emphasis being on the tribological performance leading to scuffing. In the case of unlubricated experiments [5], it was shown that scuffing was caused by plastic flow and propagation of voids and cracks from the subsurface leading to the removal of a transformed top layer of material. Similar conclusions were reached for boundary/mixed lubricated experiments.

Several research groups have reported on the tribological performance of gray cast iron. Ref. [9] reported a positive effect of phosphorus and boron addition on the wear resistance of pearlitic gray cast iron. Good tribological behavior was also reported when gray cast iron was tested against gray cast iron in a CO_2 atmosphere as compared to R134a using PAG lubricant under boundary/mixed lubricated conditions [10]. An increase in the friction coefficient was also reported with an increase in the percentage of graphite

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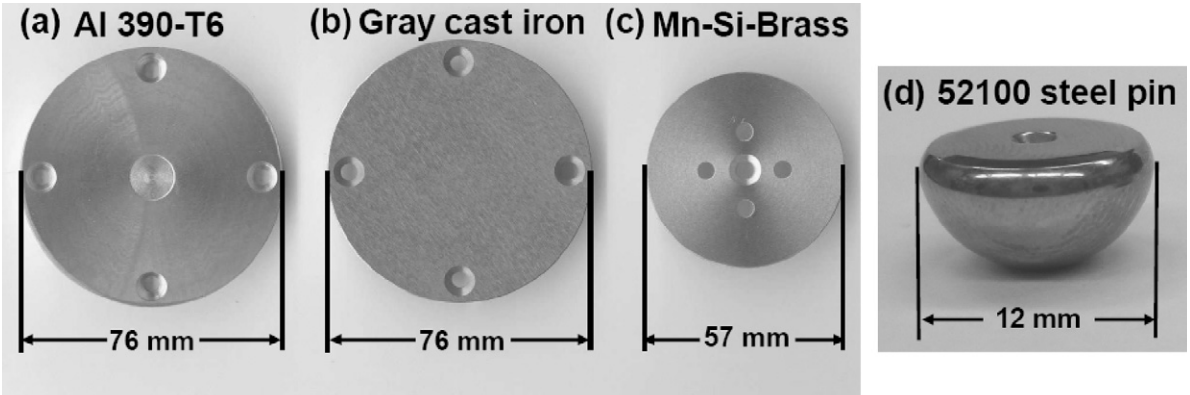

Fig. 1. Samples used for the scuffing experiments (a)–(c) disk materials and (d) crowned steel pin.

phase in gray cast iron disks (tested against linings containing steel fibers) [11]. In this case it was proposed that the friction coefficient increased due to the interaction between sharp corners of the graphite flakes and the steel fibers present in the linings.

Mn–Si brass is a high tensile brass commonly used for applications where good resistance and low friction coefficient is required as for example in automotive synchronizers in gearboxes, where the tribological performance was reported to depend on hardness and relative fraction of its α and β phases [12]. It was reported that wear originated from the detachment of hard Mn_5Si_3 particles which resulted in material weakening. In a separate study it was reported that an increase in the α phase increased the wear resistance [13].

The objective of this study is to perform a comparative investigation of the tribological scuffing performance of Al390-T6, gray cast iron, and Mn–Si brass in CO_2 refrigerant. Compressor conditions were simulated using a specialized high pressure tribometer [14] under boundary/mixed lubrication conditions using PAG lubricant. The scuffed surfaces were analyzed using scanning electron microscopy (SEM), electron dispersive spectroscopy (EDS), and X-ray photoelectron spectroscopy (XPS) to identify the chemical nature of the formed tribolayers and their lubricity effect.

2. Experimental procedure

2.1. Controlled tribological experiments

Using a specialized high pressure tribometer [6,14,15] in pin-on-disk configuration, a set of scuffing experiments were performed where the scuffing resistance was determined by progressively increasing the normal load up to the point of failure. The PAG lubricant (Idemitsu Kosan Co., Ltd., PZ 68ZL) used in this study was specifically manufactured for use with CO_2.

Experiments were performed on Al390-T6, gray cast iron, and Mn–Si brass disks tested against swash plate compressor 52,100 steel pins. The tests were performed at room temperature (22 °C) to minimize viscosity changes with temperature. Before each experiment a small amount of 40 mg of PAG lubricant (approximately 2 drops) was applied onto the surface of the pins. The normal load was increased in steps of 67 N every 15 s up to the point of scuffing. A rotational speed of 1000 rpm, corresponding to a linear speed of 2.4 m/s was used and the CO_2 chamber pressure was kept constant at 0.17 MPa. During the experiments the scuffing point was characterized by a sudden increase in the friction coefficient manifested through the formation of cold welds between the pin and the disk.

The chamber pressure used during the experiments is lower than typical pressures experienced by CO_2 compressors, which are around 3.0 MPa and 12.0 MPa for the compressor low and high pressure sides, respectively. The reason for using lower chamber pressures, other than the fact that is convenient, is justified since during boundary/mixed lubrication experiments using CO_2 refrigerant and PAG lubricant, the effect of CO_2 pressure on viscosity is relatively small. This can be explained by the partial solubility between PAG lubricant and CO_2. Such measurements reported in Refs. [17,18] show that the amount of CO_2 that can be dissolved in PAG lubricant is limited and the viscosity of PAG lubricant does not decrease significantly as a function of the CO_2 pressure (keeping the temperature approximately constant). Furthermore, the selection of low chamber pressure can be justified based on earlier tribological studies [3] at high CO_2 working pressures (boundary/mixed lubrication conditions in the presence of PAG) where no significant differences were found in terms of friction coefficient and wear after testing at CO_2 chamber pressures of 1.4, 4.1, and 6.9 MPa.

In past experiments under similar operating conditions [10], measurements of near contact temperature (subsurface temperature measured 2 mm below the sliding interface) showed that the temperature remained steady after the running-in period and only showed a sudden increase at the onset of scuffing. This suggests that after the running-in period, the lubricant film and CO_2 lubricity become stable thus significantly reducing asperity interactions and thus high flash temperatures, which could affect the lubricant viscosity.

Before each experiment the samples were immersed in a pool of acetone and ultrasonically cleaned, then rinsed with alcohol and dried using warm air. To ensure repeatability, each experiment was performed at least twice. In the contact geometry used for these experiments, the pin was the lower stationary part, and the disk was the upper rotating part. Photographs of typical tested samples are shown in Fig. 1. Note that the 52,100 steel pins are curved or "crowned" with a radius of curvature of 0.3 m and also have a dimpled geometry that helps retain lubricant during sliding [16].

To obtain similar surface roughness, all disks were machined and polished using the same technique, namely lapping. The root-mean square roughness of the samples was determined using 10 mm and 1 mm long profilometric scans for the disks and pins, respectively. After testing, cross-sections of Al390-T6, gray cast iron, and Mn–Si brass were prepared by cutting the samples exposing the cross-section of the wear tracks, then polishing using different grit emery papers ranging in ANSI standard grit size from 320 to 4000. Final mirror polishing was performed using an emery cloth. The samples were used to take SEM cross-section images.

2.2. EDS

EDS experiments were conducted on a high resolution, field emission JEOL 7000F SEM. The electron source is a Schottky field