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A study on graphite extrusion phenomenon under the sliding wear response of cast iron using microindentation and microscratch techniques

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ABSTRACT

This study focuses on the graphite flakes extrusion mechanism during microindenting and microscratching of cast iron. Observations on the graphite response under abrasive conditions revealed that the matrix deformation which is occurred during a sliding wear condition could have a significant influence on its lubricating performance. Simple microindentation and microscratch tests were conducted to explore the lamellar graphite contribution to tribofilm formation under abrasive wear conditions. The results obtained showed that induced plastic deformation which developed adjacent to the graphite compressed the lamellas and in turn resulting in extrusion of the graphite from its natural position. Further investigations on both indentation and scratch tests indicated that, surprisingly, the graphite began to be fractured and extruded from the centre of graphite lamellas, irrespective of the lamella size. Additionally, a mechanism was proposed to explain the self-lubricating and the extrusion behaviour of the lamellar graphite as a result of indentation.

1. Introduction

Generally speaking, cast iron can be considered to be a self-lubricating metal–base composite material [1]. Hence, traditionally lamellar graphite iron has been used in variant tribological applications, especially, in situations where encountering the sliding motion such as disc brakes and clutch systems [2,3]. The other application where excellent tribological performance is of great importance is piston ring-cylinder liner system. Improvements in the tribological behaviour of cast iron are primarily attributed to factors such as microstructure and graphite morphology. Prasad [4] investigated the effect of microstructures in terms of the amount of ferrite, pearlite, and graphite on wear characteristics. He also performed more studies of the influence of graphite characteristic on wear properties in terms of morphology (lamellar and spheroidal), size, content, and distribution on sliding wear surfaces. Furthermore, he indicated that lamellar cast iron (predominately that with a pearlitic matrix) offers significantly better wear resistance in both dry and oil-lubricated conditions than spheroidal graphite iron. Based on the investigations into the wear properties of cast iron performed by Sudarshan [5] and Taylor [6], a pearlitic A type lamellar graphite iron, with a limited quantity of ferrite, is a viable candidate for piston ring applications. Additionally, regarding the influence of hard phases on wear improvement, Eyre [3] and Nadel [7] performed valuable investigations, the conclusions of which were validated by other researchers [5,8]. They stated that hard phases stand out from the matrix on a fully run-in surface, and thereby improve the wear resistance by minimizing the direct metal to metal contact during sliding.

Regarding the effective lubricating nature of the graphite in lamellar iron, Sugishita et al., in two separate works [1,9], examined the effect of tribofilm formation under the reciprocating sliding and rolling–sliding conditions, respectively. In both studies, the friction and wear performance of lamellar cast iron were influenced by the surface graphite conditions. So that for conditions in which the graphite can easily lubricate the sliding surfaces a significant decrease, by several orders of magnitude, was observed both in coefficient of friction and wear rate. The good tribological properties of graphite is basically associated with its anisotropic structure and its weak interlayer van der Waals forces [10], as well as the fact that it provides a large lubricating surface area in the lubricant mixture during sliding. The interactions between these weak interlayers cause smearing processes and the formation of a very thin lubricating film between the sliding surfaces [10]. However, and despite this important function, the self-lubricating mechanism of lamellar iron remains ambiguous and has not been demonstrated and fully explained in scholarly literature.

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During sliding, the ease with which a graphite particle can be extruded from its embedded position is directly proportional to the improvement in tribological performance [11]. In previous work [12], Ghasemi et al. found that under sliding conditions, not all graphite lamellas serve the same graphite supplying function. Some lamellas are partially or entirely covered after a given period of operational time, while others remain uncovered and lubricate the sliding surfaces. Thus, this covering tendency is of critical importance, as the consequence of a less effective smearing propensity is an increased risk of incidences of scuffing or other issues associated with poor tribological properties. In the same study, the relationship between lamellar graphite orientation and covering tendency during sliding was investigated; this demonstrated that graphite lamellas that are parallel or close to the sliding direction are more easily covered than those oriented away from the sliding direction. However, the metal matrix deformation and consequent effect on the graphite as a result of sliding remain ambiguous.

The abrasive wear behaviour of lamellar irons has been studied, using scratch testing techniques, by Mendas et al. [13]. They investigated the effect of microstructure, applied various loads and attack angles of conical indenter on coefficient of friction and wear characteristics. According to the results obtained, graphite plays an important role in affecting the wear performance of the specimens. Additionally, Nakamura et al. [14], in examining lamellar iron abrasion patterns, demonstrated that sliding surfaces which are in contact only interact within a micro localized area. They further demonstrated that the graphite film that is formed on the micro scale is identical to that on the macro scale. Consequently, it derives the attentions for those who attempt to conduct further research into the nature of graphite film formation and its corresponding mechanisms to do so on the micro, rather than macro scale. A single micro contact, when subjected to a typical abrasive particle, can cause the macroscopic contact, and so the interaction of a single hard particle can be used to study and explain the macroscopic wear characteristics of a used lamellar iron component.

Any circumstance which results in or exacerbates a scratch on the matrix, particularly in the vicinity of the lamellar graphite, can cause major elastic and plastic deformation in the matrix during sliding. This can be seen in Fig. 1(a) which corresponds to a real worn surface achieved after 16,000 h operates as marine diesel engine piston ring. As known, the hard abrasive particles present in the piston ring-cylinder liner sliding system are originated either from the fuel catalyst (CAT) fines [15] or produced as the consequence of adhesive or corrosive wear (i.e. oxides/debris) [16] which were analysed by energy dispersive X-ray spectroscopy (EDS) technique and shown in Fig. 1(b) and (c), respectively. CAT fines are considered to be impurities which are present in heavy fuel oil, and result from catalytic cracking during the oil refining process. Hard aluminium silicate particles in various forms, sizes, and hardness ranges are used during the catalytic cracking process [15]. This interaction between the hard particles, matrix, and graphite should be thoroughly taken into consideration in a situation where a continuous supplying of graphite is required. According to Jones et al. [17], a moderate to high concentration of these hard particles may significantly impact on the wear behaviour of the sliding surfaces, in turn resulting in excessive wear to fuel pumps, cylinder liners, and piston rings. From this viewpoint, a single asperity or piece of debris may either indent a mating elastic surface, or become flattened during sliding [18].

The present study investigates the interactions between the hard abrasive particles and graphite lamellas. Microindentation and microscratch testing were carried out in order to understand and explore the matrix and lamellar graphite response, as well as the ways in which graphite may act to lubricate sliding surfaces when it is subjected to abrasive particles.

2. Experimental procedure

2.1. Materials

Two pearlitic lamellar graphite iron piston ring segments, which were sectioned from a marine diesel engine running with heavy fuel oil, were used in the study. Table 1 presents the chemical composition of the tested materials.

2.2. Microstructural analysis

To examine the microstructure, the specimens were ground and then polished metallographically using diamond paste, following a standard sample preparation procedure down to a 3 µm finish. A 2% Nital solution was used for etching. The etched microstructures were

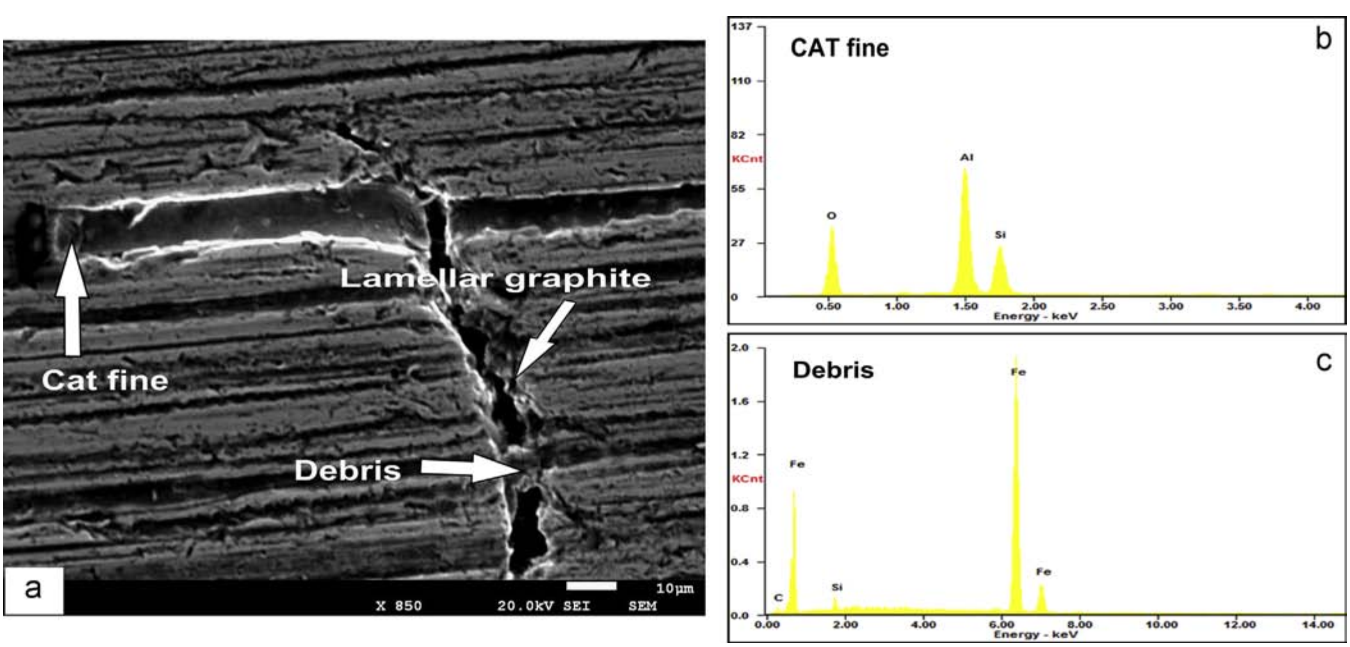

Fig. 1. SEM image indicating the presence of a CAT fine and wear debris entrapped in the lamellar graphite, along with corresponding EDS spectra.