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The relationship between flake graphite orientation, smearing effect, and closing tendency under abrasive wear conditions

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A B S T R A C T

Plastic deformation of the matrix during the wear process results in closing the graphite flakes. In this study, the relationship between the deformation of the matrix and the closing tendency of flake graphite was investigated, both qualitatively and quantitatively. Two representative piston rings, which belonged to the same two-stroke marine engine but were operated for different periods of time, were studied. Initial microstructural observations indicated a uniform distribution of graphite flakes on unworn surfaces, whereas worn surfaces demonstrated a tendency towards a preferred orientation. Approximately 40% of the open flakes of the unworn surfaces were closed during sliding, which may result in the deterioration of the self-lubricating capability of cast iron. Moreover, flakes within the orientation range of 0 to 30° relative to the sliding direction showed a maximum closing tendency when subjected to sliding. The closing tendency gradually decreased as the angle increased, approaching a minimum between 30 and 70°. A slight increase in the closing tendency was observed for flakes with orientations between 70 and 90°. A similar trend was observed on both rings. Furthermore, SEM and EDS analysis indicated substantial deformation of the matrix in the area around the flakes. An insignificant corrosion attack was observed on both worn piston ring surfaces.

1. Introduction

Over the years, grey cast iron (GCI) components have commonly been used in a variety of tribological applications, particularly in systems involving sliding, such as disc brakes, clutch and piston rings, and cylinder liner systems [1]. In tribological terms, the operating conditions for piston rings bring about a complex wear situation caused by high temperature, pressure, and mechanical friction, all of which contribute to multifaceted, high-stress conditions [2]. The oil lubrication system, clearance, initial surface roughness [3], and microstructure of the materials used [4] are other critical factors for high performance piston ring-cylinder liner materials. Low production costs, excellent tribological performance, superior machinability, outstanding thermal conductivity, and high wear resistance, for both lubricated and dry sliding conditions, [5] have made GCI a great material for such complex applications [6].

From the tribological point of view, the excellent wear resistance of GCI stems from the self-lubricating nature of the graphite particles which are distributed as flakes throughout the matrix. During sliding, carbon atoms are released from the graphite pocket, smeared onto the surfaces, and serve as solid lubricating agents by forming a thin graphite film between the sliding surfaces [7,8]. Formation of tribofilm results in a decrease in specific wear rate by several orders of magnitude, as it limits direct contact between the sliding surfaces [7–9]. In addition, the graphite flake sites act as oil reservoirs, improving the supply of oil between sliding parts during dry starts or similar conditions involving oil starvation [9]. The advantageous contributions of open graphite flakes have been highlighted by Sugishita and Fujiyoshi [10].

For many years, the high wear rate reported in piston rings-cylinder liner systems seemed to be associated with the presence of a high sulphur content in the fuel. The presence of sulphur leads to a corrosive environment through the formation of sulphuric acid on the liner wall, which in turn accelerates the wear rate during sliding. Recently, however, it has been reported that the high wear rate and surface degradation of the piston rings are related to abrasion and scuffing, rather than corrosive wear [6]. In most investigated applications, the wear process proves to be significantly more complex than expected [11]. Scuffing occurs when a strong adhesive force develops between the piston rings and the cylinder liner under non-optimal lubrication conditions. As reported, scuffing happening is almost always accompanied by a substantial increase in friction [9], with a severe plastic deformation of the matrix [6]. The occurrence of scuffing is shown by

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micro-welding and/or severe wear scars, which represent plastic deformation, abrasive ploughing, and adhesive wear [12]. As has been proven so far, a direct relationship exists between the increased volume of graphite on the sliding surface and decrease in specific wear rate, discussed by Sugishita [13].

Abrasion plays a major role in sliding wear conditions by changing the matrix texture during sliding [12,14]. Montgomery has studied the importance of matrix deformation under abrasive wear conditions, including both fully lubricated and dry sliding conditions [15,16]. He reports that the formation of a graphite film significantly reduced the risk of scuffing under abrasive conditions by ploughing the metal matrix. Eyre et al. [14] indicated a dramatic increase in wear rate in piston rings and cylinder liner caused by abrasive wear. The hard abrasive particles could either be introduced into the system by the fuel in the form of catalyst fines (CAT fines), or be present as a wear-produced particles (debris) [6,17]. A study performed by Riahi [17] showed that plastic deformation of the matrix accelerates debris formation.

The abrasive particles are sufficiently hard to indent and scratch the sliding surfaces, which leads to severe plastic deformation of the metal matrix [12]. Apart from the microstructural standpoint the presence of the phases so as carbides and phosphides, graphite morphology and graphite flakes play important roles under abrasive condition [17–19]. The orientation of the graphite beneath the sliding surface affects the wear behaviour of the cast iron as it alters the deformation tendency in the matrix around the flake [20]. Micro-interactions, including micro-ploughing and micro-cutting; between abrasive particles and the matrix may also cause the graphite flakes to close [10], detrimentally deteriorates the self-lubricating performance of the cast iron. Therefore, keeping the graphite flakes open during sliding is tribologically beneficial, as their lubricating effect is retained.

The aim of this study is to investigate the relationship between flake graphite orientation and plastic deformation in a cast iron matrix during sliding conditions. An understanding of this relationship clarifies the deformation response of the flakes and the matrix when the piston ring is subjected to sliding and abrasive wear conditions. Both qualitative microscopic observations and quantitative measurements of the graphite distribution of worn samples are considered.

2. Materials and methods

2.1. Piston rings from a large two-stroke marine diesel engine

The rings used in this study were 800 mm in diameter and designed for two-stroke marine engines, as shown in Fig. 1 (a). The outer surface of the as-cast piston rings are essentially horizontally machined roughly 3 mm before applying the coating. This step is performed to remove the skin defects (undesired structure) from the surface. The surface roughness average (Ra) of the rings are checked to be within 3.2–6.3 μm before coating. Fig. 1 (b) illustrates the as-manufactured ring surface without coating. The piston rings were protected by two different types of thermally sprayed coatings, including cermet and aluminium-coating. The coatings and base material specifications for each of the piston rings are given in Table 1 [21].

Cermet is a composite material which is used for hard coating, and consists of a ceramic part (chromium carbide) and a metallic part (molybdenum, nickel, and chrome). Aluminium-coating (a bronze-based coating containing alumina oxide insoluble, which was first introduced by MAN B&W Diesel A/S) was used as a semisoft running-in coating. The running-in coating is thermally deposited over the hard coating in order to shorten the running-in time, improve sliding characteristics, and increase scuffing resistance during the running-in period. The aluminium-coating provides a smooth and profiled running-in surface, and is gradually worn off until it is entirely removed approximately after 1–2,000 h.

As the location of the second piston ring subjects to more severe wear conditions (e.g. higher temperature and pressure) than the third and fourth rings, it was selected for the present investigation. The chemical composition of the rings is presented in Table 2. The piston ring segments were provided by MAN Diesel and Turbo.

2.2. Sample preparation

The present investigation was carried out on two different piston ring specimens extracted from the same ship engine, but were running for different time periods; approximately 16,000 and 20,000 h. Both rings had a good run-in condition and had

Table 1
Specifications for the piston rings [21].

Piston ring	Base material	Hard coating Cermet thickness (mm)	Running-in coating Aluminium-coat thickness (mm)
First	Compacted graphite iron	0.5	0.1
Second	Grey cast iron	–	0.3
Third	Grey cast iron	–	0.3
Fourth	Grey cast iron	0.3	0.1

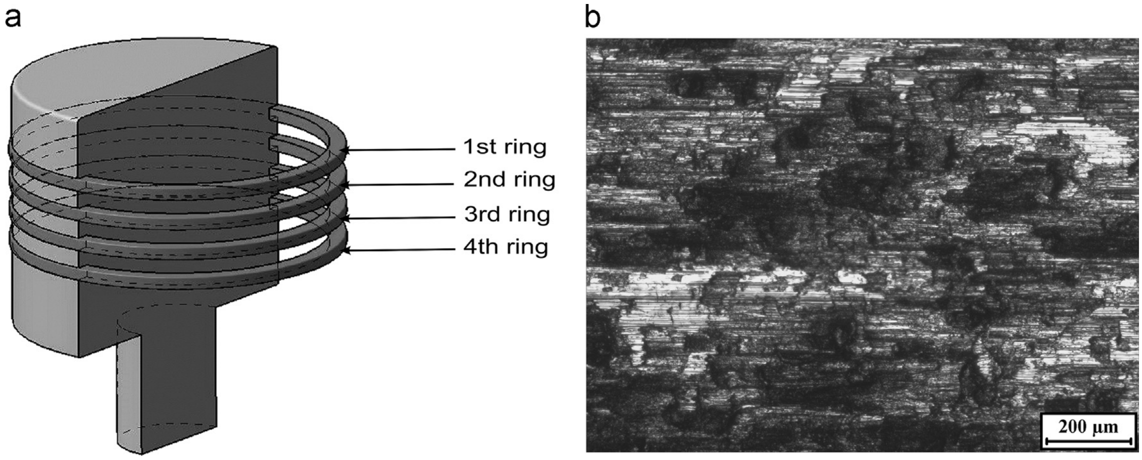

Fig. 1. (a) Schematic of a typical piston ring pack with four rings; (b) typical surface appearance of the as-manufactured piston rings before applying coating.