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Abrasion Resistance of Lamellar Graphite Iron: Interaction Between Microstructure and Abrasive Particles

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Abstract

This study focuses on abrasion resistance of Lamellar Graphite Iron (LGI) using microscratch test under constant and progressive load conditions. The interactions between a semi-spherical abrasive particle, cast iron matrix and graphite lamellas were physically simulated using a sphero-conical indenter. The produced scratches were analysed using LOM and SEM to scrutinise the effect of normal load on resulting scratch depth, width, frictional force, friction coefficient and deformation mechanism of matrix during scratching. Results showed a significant matrix deformation, and change both in frictional force and friction coefficient by increase of scratch load. Furthermore, it was shown how abrasive particles might produce deep scratches with severe matrix deformation which could result in graphite lamella's coverage and thereby deteriorate LGI's abrasion resistance.

Keywords: Lamellar graphite cast iron, abrasion resistance, scratch test, microstructure, pearlite deformation

1 Introduction

Lamellar Graphite Iron (LGI) alloys are commonly used in applications such as piston rings and cylinder liners in heavy-fuel marine diesel engines, where an excellent combination of thermal and tribological properties are required [1, 2]. The self-lubricating performance of LGI is basically due to the presence of graphite lamellas in the microstructure, in which, under sliding condition, the graphite particles are worn out and the graphite residues end up onto the tribosurfaces. This lubricating film formation mechanism; thereby, improves the wear response of sliding system by decreasing friction and specific wear rate [3]. In addition, the smearing process of the graphite between the sliding surfaces results in reducing of scuffing and seizure risks as well [4, 5]. It is well-understood that it is tribologically beneficial and is an essential solution to keep the graphite particles open on the sliding surfaces in order to avoid scuffing, especially under unlubricated or

poor lubricated sliding conditions [3]. However, previous studies showed that a large portion of the lamellas are covered under sliding conditions as a result of severe matrix deformation caused by both abrasive and adhesive wear mechanisms [6, 7]. It should be noted that abrasion caused by hard solid particle contaminations, known as cat-fines, is the one of the key reasons for critical damage and marine diesel engines failures [1, 7]. A single large solid particle may lead directly to a system malfunction, while small particles may cause a continuous elevated wear [8]. Thus, apart from the surface texture of the materials, special care should be taken to ensure that critical factors such as fuel treatment and oil cleaning are controlled continuously [9, 10]. In addition, scuffing is more probable in the **Top Dead Centre (TDC)** region of a combustion chamber, where both adhesion and abrasion cause severe plastic deformation of the matrix [11, 12]. Scuffing occurs in poor lubricating regions such as TDC results in a dramatic increase of friction [13], due to the lack of lubricant and covering of a large portion of the graphite lamellas; thereby, deteriorates the overall self-lubricating performance of the sliding cast iron parts [14]. The effect of operating parameters such as applied load, sliding speed, and lubrication on tribological behaviour of cast iron alloys have extensively been studied [10, 15, 16]. However, very few studies have been made to explain and correlate microstructural features with abrasion resistance of cast iron components with special focus on piston rings-cylinder liner in heavy-fuel diesel engine applications. Hence, an in-depth understanding of the relationship between microstructure, mechanical and tribological properties could help engine designers and manufacturers to develop cast iron engine components with improved mechanical and tribological performance.

Scratch testing has traditionally been employed to characterise the coating-substrate adhesion strength [17] and scratch resistance of different coatings [18] and polymers [19, 20]. Noticing that surface scratching is a complex process especially when a cast iron that has a composite nature is involved [21]. In the case of bulk materials, the scratch test has recently been used to evaluate the surface mechanical properties such as scratch hardness [22, 23] and to determine the fracture toughness [24, 25]. Even though abrasion is a very complex mechanism, scratch test is a valuable tool to characterise the abrasion and wear resistance of various materials, thus mimicking low or severe abrasion [26]. In a typical single-pass scratch test, a controlled normal force is imposed to an indenter (diamond stylus) of defined geometry and allowed to move at a specific speed over the work piece surface to scratch and produce mechanical deformation [27, 28]. The induced tangential and normal forces as well as the resulting scratch morphology are correspondingly analysed to assess the surface mechanical properties and scratch resistance of the bulk material. These findings enable us to crudely simulate the interaction between a single spherical hard particle (cat-fine), the cast iron matrix and the graphite as well as examine the related matrix deformation under abrasion.

The main objective of this study is to correlate the experimental results obtained from the microscratch testing and scratched surface analyses with microstructural features to determine the abrasion resistance of LGI. The SEM imaging was used to study the interaction between abrasive particles (cast-fines/debris) and microstructure, by evaluating the wear damage and related matrix deformation mechanisms during scratching.

2 Experimental procedure

2.1 Materials and sample preparation

An alloyed pearlitic LGI cut from a large bore heavy-fuel two-stroke marine diesel engine piston ring, shown in **Figure 1(a)**, with a typical composition given in **Table 1**, was selected for this study.

Table 1. Chemical composition of the LGI piston ring sample investigated (wt. %).

C	Si	Mn	Ni	Mo	Co	Ti	Cr	V	S	P	C _{eq}
3.30	1.55	0.85	0.35	0.60	0.85	0.07	0.15	0.15	0.08	0.10	3.84

$$\text{Carbon equivalent (C}_{eq}\text{)} = \text{C}\% + (\text{Si}\% + \text{P}\%)/3.$$

Specimens with dimensions of 20 mm × 20 mm × 15 mm were metallographically ground with silicon carbide papers progressively, followed by polishing down to 1 µm diamond paste. The polished specimen was then cleaned with acetone in an ultrasonic cleaner prior to scratch testing. This was done to exclude any surface roughness feature's influence on the scratching marks and results. The sample surface prepared for scratch test had a surface roughness (Ra) of approximately 0.02 µm. In cases where studying the pearlitic deformation were of interest, the polished surface was very gently etched using Nital solution 2% before scratch testing.

Figure 1. SEM micrographs representing (a) microstructure of a typical pearlitic lamellar graphite iron before scratching, (b) scratched produced in actual piston ring because of interaction between cat-fine particle, matrix and graphite lamella.

A typical in-service interaction between a cat-fine particle and the cast iron microstructure is shown in **Figure 1(b)**. This surface corresponds to the piston ring surface facing the cylinder liner. Detailed microstructural investigations and scratched surface analyses were performed using a Light Optical

Microscopy (LOM), Olympus, and Scanning Electron Microscopy (SEM), JSM 7001F. The non-contact 3D profilometer was performed using Alicona Mex-Professional reconstruction software in TESCAN LYRA3 SEM for scratch depth and scratch profile analysis.

2.2 Microscratch testing

Scratch resistance (in this case abrasion resistance of the LGI) was characterised by conducting a single-pass scratch test using an instrumented micro and nanoscratch apparatus developed at Micro-materials NanoTest system. The employed apparatus, (**Figure 2(a)**), is equipped with an optical microscope, tangential friction force and penetration depth sensors. To perform the scratch test, the specimen is fixed to a holder on a positioning table, which moves vertically in the z-axis up or down, whilst the contact load can be either held constant or progressive at a user-defined rate. During scratching, the depth of penetration (d_p) and frictional (tangential) force are continuously recorded.

Figure 2. (a) Schematic drawing of micro and nanoindentation, and scratch test set up; (b) Schematic representation of abrasive particle with a sphero-conical tip geometry.

An indenter with a defined geometry, which can be modelled as a single asperity or semi-spherical cat-fine particle in abrasive type of wear mechanism was used to investigate the nature of the microstructure's (mainly matrix and graphite) failure events under scratching (abrasion). A diamond indenter with a sphero-conical tip (nominal radius 25 μm) and having a cone angle of $2\theta = 90^\circ$, as schematically illustrated in **Figure 2(b)**, was used for scratching the surfaces. The scratch tests were conducted in accordance with ISO 14577-1:2002 standard at room temperature $\sim 25^\circ\text{C}$ under constant and progressively increasing normal loading conditions. The pre- and post-topographies with a scanning load of 0.2 mN were conducted to determine the surface topography of the surface

prior to the scratching and measure the residual groove depth after elastic recovery, respectively. At least three scratches were performed on LGI under progressive load conditions and the average data are reported in this study. The scratch depth was measured relative to the surface profile before scratching. The average scratch width was measured using the SEM images.

2.3 Scratch hardness

For viscoelastic-plastic materials, the recovered material will partially support the rear half of the indenter tip in the trailing zone as it moves forward, however the material's rate of recovery and the imposed scratch velocity significantly influence this support. Recovered scratch width data were further used to compute scratch hardness. For a general viscoelastic plastic-material, such as LGI alloys, the scratch hardness HS_p is approximately defined by **Eq. (1)** [19]:

$$HS_p \approx \frac{F_n}{A} \approx q \frac{4F_n}{(\pi W^2)} \quad (1)$$

where A is the projected area supporting the normal load, F_n is the normal load applied to the indenter tip, W is the recovered width of the scratch and the parameter q varies according to test material's response ($q \approx 2$ for rigid plastic materials and a plastic deformation case when the load is only supported on the front face of the indenter and $q \approx 1$ for viscoelastic materials). Note should be taken that the scratching velocity and the geometry of indenter are the other parameters that influence the q value. The corresponding q value for a plastic deformation is $q=2$.

3 Results and discussion

3.1 Constant load microscratch testing

Figure 1(b) represents a severely abraded LGI surface caused by a cat-fine particle, which was detected on the actual worn out piston ring samples studied. As can be seen, the abrasion process was accompanied by micro-ploughing, which resulted in a severe matrix displacement/deformation to the sliding surfaces. This observation showed that if these hard asperities come in contact with piston rings and cylinder liner surfaces, they can easily produce deep scratches on the surfaces. Such an interaction could significantly change the topmost metal matrix surface layers and thereby deteriorates lubricating capability of the graphite lamellas under sliding conditions.

In the present investigation, as the first attempt, the constant load scratch tests (A and B) were performed over a typical graphite lamella. Note should be taken that degree of approximation of speed and materials properties, lubricating condition and its rate dependence temperatures and so forth are still far from the real combustion chamber. The 1000 mN applied normal load on a sphero-conical indenter radius of 50 μm , results in contact pressure of about 130 MPa, which is similar to the scuffing load as determined as extreme pressure in large bore low-speed two-stroke marine

diesel engine. In real ring and cylinder liner system, the conventional contact pressure is 15-20 MPa [13]. Scratches (of length 300 μm) were made employing a constant load with scanning velocity of 10 $\mu\text{m/s}$ and pre- and post-scan topography forces of 0.2 mN. A load of 1000 mN corresponded to a residual scratch width of $\sim 35 \mu\text{m}$. The SEM images shown in **Figure 3(a)** and **(b)** highlight the common responses of graphite lamellas under scratching and how they could contribute to lubricate the sliding surface under abrasion conditions, respectively.

Figure 3. (a) Scratched surface of a typical lamellar graphite sample; (b) showing the extrusion and fracture behaviour of graphite lamella under scratching. For both scratches a load of 1000 mN was employed. Scratch direction is from bottom to top.

According to Mendas et al. [29], under abrasion and sliding conditions the graphite particles are smeared in front of the hard particles (indenter) and act as self-lubricating agents by decreasing the friction coefficient. However, in our study it was often observed that the graphite lamellas were primarily fractured from the centre and then extruded, as marked in **Figure 3(b)**, and more specifically got covered because of severe matrix deformation occurring in the course of scratching rather serve their smearing effect and lubricating performance. Furthermore, under 1000 mN, the scratches' interactions with the graphite lamellas and metal matrix were mainly governed by ploughing and no metal chips formation in front of the indenter. The chips formation phenomenon next to the wear groove was also detected on the edges of the scratches. In addition, at the bottom of the scratch track B, delamination of the matrix (controlled by a stick-slip mechanism) is visible, as identified by black dashed rectangular area in **Figure 3(a)**.

As the indenter passed the graphite lamella, a part of the affected volume of the grooves were displaced sideways to the edges. This was accompanied with an extensive plastic deformation of the matrix, pile-ups formation, without inducing micro-cracking, while this interaction was not detected before the indenter faced the graphite. This observation indicates that the removal of material mainly occurred first by micro-ploughing and then partially by micro-cutting mechanism. As an interesting phenomenon, it was noted that a similar fracture and extrusion behaviour accompanied

by empty pocket formation and crack initiation near the scratches occurred during scratching as compared to our earlier study using microindentation techniques [30]; see **Figure 3(b)**. In this failure mode, the graphite layers were first folded and then the cracks were formed in the centre of the graphite lamellas.

Figure 4. (a) Scratch depth and frictional force, (b) scratch depth and friction coefficient profiles correspond to the scratch B conducted over the graphite lamella. A constant scratch load of 1000 mN was employed.

Figure 4(a) and **(b)** present the scratch depth, post-scratch topography, frictional force and friction coefficient, respectively, measured during the scratch B performed on graphite lamellas, as presented in **Figure 3(a)**. The similar behaviour was observed in scratch A. The black solid and red dashed lines show the scratch depth during scratching and the residual (plastic) depth once the scratch load has been removed, respectively. These have been corrected for initial sample topography, shown by black dotted line. The frictional force and friction coefficient values are shown in **Figure 4(a)** and **(b)** by blue dashed-dot and green dashed-dot-dot profiles, respectively. The difference between the scratch depth and post-scratch topography give an idea of the significance of the elastic recovery happened in the matrix once the applied load was released. Note should be taken that the positive y-axis has been selected as reference for scratch depth (indenter's depth of penetration).

As expected, under an individual constant scratch load, the elastic recovery of a uniform material should not be changed providing that the indenter cross over the matrix with the same characteristics, as can be identified for the scratch length of about 130 μm to 210 μm. However, in this case, the indenter faces different microconstituent (such as pearlite with different inter-lamellar spacings structure which could be one reason for such strange increase of elastic recovery after 210 μm. The other possible explanation for a very small plastic deformation recorded during the experiment, over 210 μm, could be explained by the limitation of sphero-conical shape and size of the indenter used for post-scan topography measurement after induced scratching, in particular, at the end of the scratch. Hence, in order to properly evaluate the elastic recovery and plastic

deformation non-contact surface profilometer, as will be presented in section 3.2.3, is preferred which will be extensively discussed in upcoming work. Furthermore, it has been discussed by Kataria et al. [31] that larger plastic deformation is accompanied with reduced elastic recovery at higher scratch loads and at higher scratch speeds, plastic deformation rates are higher which caused friction coefficient to be of higher magnitude.

As can be observed, as the scratch proceeded, the depth of penetration was increased and reached maximum in the middle of the graphite lamella. Then, it was decreased while the indenter moved onwards the graphite and faced the pearlitic metal matrix again. This interaction can be linked to the change of frictional force so, as the scratch proceeds, the frictional force increases, however, it significantly dropped as the indenter faced the graphite. As can be observed in **Figure 4(b)**, the friction coefficient was following the same trend as explained for the frictional force. One reason could be correlated to the graphite lamella's orientation beneath the surface and described by the less amount of metal matrix beneath the indenter in this region, as reported previously [32]; thus, the metal matrix could not fully support the applied load during scratching. This is visible from the characteristic of the scratch scare just before the graphite. Moreover, the frictional force, and consequently friction coefficient, increased just on the other side of the graphite lamella again, approaching the maximum value because of the edge effect of the graphite/matrix interface. Further scratching was carried out with a slight decrease in frictional force and friction coefficient. This phenomenon was accordingly observed together with delamination of iron metallic matrix and debris formation on the side of the scratch track, as marked in **Figure 3(a)**.

3.2 Progressive load microscratch testing

In general, scratch test under constant load offers a good understanding of materials failure under abrasion condition. While the biggest advantage of progressive load scratch testing is to study the evolution of material deformation characteristics during contact sliding conditions. Moreover progressive scratching enables to identify the critical loads for various failure mechanisms [33]. In this part of the investigation the scratch resistance and related deformation responses of graphite lamellas, carbides and pearlite matrix were studied.

3.2.1 Graphite lamellas failure mode

Figure 5(a) and **(c)** present the two graphite lamellas selected in this study to perform scratch testing alongside them. This was carried out to examine the fracture and lubricating behaviour of graphite lamellas when they are subjected to the matrix deformation resulted from abrasion, in this case by scratching. The scratch load was applied in a progressive manner from 5 mN up to 2000 mN, and 3000 mN in order to monitor the onset of the graphite fracture and/or push-out

phenomenon of graphite under abrasion. The scratches were conducted on the metal matrix $\sim 40 \mu\text{m}$ away from the graphite lamellas. The selection of this range of load was mostly based on their relative importance in piston rings and cylinder liner and industrial usages to crudely mimic the abrasion condition caused by a typical spherical cat-fine particle. This scratch condition was chosen by taking into the consideration the cat-fine's sizes and shapes as well as the pressure developed on TDC region of the combustion chamber [13], similar to what was observed earlier in **Figure 1(b)**.

Figure 5. LOM images showing the graphite lamellas appearance: (a), (c) before scratching; and (b), (d) after employing scratches. Scratch directions are from left to right.

The characteristic influences of applied load on plastic deformation occurring during scratching, and lubricating performance of graphite lamellas are demonstrated in **Figure 5(b)** and **(d)**. As can be seen, under progressive load condition, 5mN to 1500 mN (**Figure 5(b)**), the graphite lamella remained unaffected. While in the other case (**Figure 5(d)**), further increase of scratch load to 3000 mN was high enough to fracture the graphite lamella. This was because the material in contact with the tip of indenter, was deformed (compressed) sideways and thereby pressed the graphite lamella in a successive manner. As the tip of the indenter penetrated deeper into the material, the material was pushed away. The evidence of the fractured graphite lamellas is found on the scratch made under progressive normal load of 5 mN to 3000 mN as marked by the white tracks in **Figure 5(d)**.

Further increase of the scratch normal load resulted in activation of the graphite extrusion phenomenon and thereby acting as self-lubricating agent during sliding. Such behaviour was due to

the excessive deformation of matrix, which occurred around the scratch groove as a result of scratching the metal matrix. Accordingly, for such a scratch distance, slightly over the 2000 mN load was found as the threshold of yielding the graphite lamellas in LGI under abrasion. Nevertheless, it is obvious that the closer the scratching to the lamellas is, the less normal load would be required to fracture the graphite lamellas. Furthermore, increasing the applied load would result in extrusion of the graphite from its pocket, as discussed in our previous work [30].

3.2.2 Microstructural deformation mechanisms

In the present study, the scratch testing technique was utilised to also correlate the microstructural features with abrasion resistance of a typical lamellar cast iron material. In the case of bulk materials, progressive load scratch test is a suitable method to investigate the critical scratch normal loads which cause the cohesive failures, such as cracking, or plastic deformation of the studied material which affect the overall tribological performance of the material.

Figure 6. (a) Pre-, post-scan topography and scratch depth profiles corresponds to scratch No. III ; (b) SEM micrograph showing full scratches performed on LGI under progressive load ranging from 5 mN to 1500 mN (No. I&II), and 5 mN to 3000 mN (No. III&IV). Scratch direction is from left to right.

For this purpose, several scratches were performed on LGI sample under progressive load conditions ranging first from 5 mN to 1500 mN (scratches No. I&II), and then 5 mN to 3000 mN (scratches No. III&IV). The actual depth of penetration at the time of scratching (scratch depth), pre- and post-scan topographies profiles versus the scratch length were recorded and typically

presented for scratch No. III in **Figure 6(a)**. The SEM micrographs showing the interactions between the indenter and the cast iron matrix and graphite lamellas for four progressive load scratches, corresponding to two different loading conditions, are shown in **Figure 6(b)**. The applied normal load, frictional force and friction coefficient values which were also continuously monitored during scratching, as plotted in **Figure 7**.

Figure 7. (a) Scratch load, frictional force and friction coefficient profiles measured during scratching correspond to scratch No. III.

Generally, in all scratches shown in **Figure 6(b)**, the introduced nominal strain caused by the sphero-conical indenter normal to the surface was sufficiently high to cause plastic yielding or fracture in the localised regions of the sample where the scratches were produced. It also showed a noticeable influence of scratch load increment on induced plastic and elastic deformation as well as failure appears in each individual phase and micro-constituents present in the microstructure. The failures corresponding to each individual phase caused by scratching can be differentiated by the scratch depth and frictional force profiles. As can be seen in **Figure 7**, the frictional force, and friction coefficient are fluctuating along the scratch path when indenter passes over different phases. Further SEM image analysis of scratch No. III was performed to obtain an in-depth understanding of how material deformation and removal processes take place during scratching. This has an outstanding consequence in better understanding of the correlation between abrasion, which takes place by hard particles or loose debris; and the influence of its produced plastic deformation on resulting tribological performance of LGI alloys. Selected regions marked by white dashed boxes in **Figure 6(b)**, and their related deformation mechanisms are presented in SEM images in **Figure 8**. The obtained results revealed a clear change in deformation mechanisms along the scratch length under different magnitude of normal loads ranging from 5 mN to 3000 mN. These effects can be seen in **Figure 8(a)-(f)**. As shown in **Figure 8(a)**, at very low load scratch the matrix deformation is

insignificant, in that the stylus just passed over the pearlite with no considerable induced deformation. However, after scratching $\sim 150\ \mu\text{m}$ of the surface (**Figure 6(b)**), which corresponds to 150 mN, a small displacement of matrix with no significant interaction with the graphite was detected, in that, the indenter just passed over the graphite lamella with marginal deformation. The plastic deformation became more pronounced at increased scratch load up to about 500 mN, which resulted in a visible deep groove with increasing scratch depth and width.

Figure 8. High magnification SEM micrographs of scratches produced on LGI sample under progressive load scratch testing ranging from 5 mN to 3000 m; indicating the interactions between indenter and various micro-constituents in the microstructure. Scratch direction is from left to right.

A continuous increase of scratch load resulted in a noticeable deformation of the pearlitic matrix, which is mainly controlled by a micro-ploughing mechanism. This is identified by the presence of ridge formation along the scratch groove as results of displacement of the matrix without physical removal of the material and metal chip formation ahead of the indenter in **Figure 8(b)**. However, at higher scratching loads, debris particles/chips are formed on the sides of the scratch track as well (**Figure 8(c)**), while the deformation mechanism is mostly controlled by a severe micro-ploughing abrasive wear mechanism.

In addition, a closer look at **Figure 8(d)** shows that increasing the normal load and therefore scratch depth, considerably increased the amount of material which was being pushed out from the stick-slip phenomenon becoming severe at higher loads. Furthermore, the micro-wedge formation mechanism could also be observed after a scratch length of 1000 μm which is valid up to 1500 μm . Whereas the transition between micro-ploughing to micro-cutting mode was accompanied with a remarkable pile-up formation and matrix failures in the form of delamination at the bottom of the scratch tracks as seen in **Figure 8(d)**. This figure shows material removal during scratching in the form of debris at loads higher than 1500 mN as well as increasing the scratch width along the scratch depth. However, some bulge or pile-up can be seen on the sides of the scratch indicating ductile deformation of the pearlite matrix. Moreover, as seen in **Figure 8(e)** and **(f)**, micro-cutting is the dominant wear mechanism when the indenter was scratching the metal matrix under loads of higher than 1500 mN, where a significant damage and severe delamination of the material on the bottom of the scratch grooves can be recognised. Similar behaviour was observed for the scratches No. I, II; however, the micro-ploughing and micro-cutting damages appeared in different locations due to the different applied loading conditions.

One of the most interesting findings of this study is that, progressive load scratch test enables to monitor the threshold load required to stimulate the graphite to extrude from its pocket, as illustrated in **Figure 8(d)**. Such observation clarifies the previous claim presented in **Figure 5** that a minimum load of about 2000 mN is essential to trigger the graphite to extrude and act as lubricating agent during abrasion.

Besides, the impacts of the metallic matrix on scratch resistance, presence of hard phases such as carbides and phosphides improve abrasion resistance, because these hard phases stand out from the matrix on a fully running-in surface, thereby enhancing wear resistance by minimising the direct metal to metal contact [1, 6, 34]. A sudden change in scratch depth, frictional force and friction coefficient profiles during scratching, as shown in **Figure 6(a)** and **Figure 7**, could be a good indicator of tracking the nature of matrix deformation mechanism, delimitation process, or the interaction between indenter and micro-constituents. This conclusion, has been confirmed by the performed scratch test (**Figure 8(e)**), where the indenter passed over a hard phase, and formed a very a narrow scratch with insignificant displacement and a significant drop in frictional force and friction coefficient values, illustrated in **Figure 7**. These findings are in accordance with results discussed in literature [1, 29, 35]. However, as **Figure 8(e)** indicates, too much applied load (about 2000 mN) could lead to damage and fracture of these hard phases. This would be very detrimental to the tribosystem as these detached particles can act as secondary abrasive particles during the

sliding process and cause severe abrasion. It is worth mentioning that in none of the scratches, cracking was observed for scratch loads up to 1500 mN and 3000 mN.

3.2.3 Scratch depth and scratch width

The effects of progressive normal load on the actual depth of penetration during scratching and residual scratch width (cross-section) profiles are presented in **Figure 9(a)** and **(b)**, respectively. A high coefficient of determination, R-squared value, is a good indicator of a good fit for these measurements. The scratch width was presented as an average of the recovered scratch width data obtained from the SEM images taken from at least three scratches. Since the scratch width was varying along the individual scratch length, a mean value of sixteen measurements correspond to sixteen different scratch positions and loads, as the data shows in **Figure 9**, has been presented for each scratch condition.

Figure 9. (a) Scratch depth; (b) scratch width corresponding to the progressive load scratch testing 5 mN to 3000 mN.

Figure 9(a) and **(b)** indicate distinctly that both the scratch depth and scratch width tend to increase with increasing the applied normal load. Comparing the depth of penetration result presented in **Figure 6(a)**, with the scratch frictional force, friction coefficient data shown in **Figure 7** and scratch depth and scratch width illustrated in **Figure 9(a)** and **(b)**, a clear change is seen in the scratch frictional force and depth profiles at about 1000 mN across the scratch length, where a significant increase of depth of penetration is noticeable. The scratch depth varied between 0.2 μm and 2.5 μm for the range of loads of 5 mN and 1000 mN, while it increased remarkably to $\sim 20 \mu\text{m}$ for a scratching load of 3000 mN. Hence, the 1000 mN load could correspond to a significant change in deformation mechanism of the material studied.

In addition, by comparing the data presented in **Figure 9(a)** and **(b)** with the SEM scratch micrographs in **Figure 6(b)**, it can be seen that the increasing normal load increases the amplitude of the frictional force fluctuation. This is because of the severe microstructural deformation mechanism occurred over the scratch length by increase of applied load, as presented in **Figure**

6(a). Furthermore, increase of scratch loads lead to a remarkable plastic deformation and surface damage to the sliding surfaces.

Figure 10. Scratched surface analysed done using SEM equipped with non-contact 3D profilometer, (a) typical 3D SEM-image, (b) colourful 3D SEM-image taken from tip of the scratch No. III corresponds to progressive applied load range of about 2800 mN to 3000 mN.

The recovered scratch depth was further validated by scratch analysis using SEM equipped with non-contact 3D profilometer. The obtained results are shown in **Figure 10(a)** and **(b)**. As can be seen a very good correlation exists between the measured depth of penetration from scratch testing, **Figure 6(a)**, and SEM scratched surface analysis, **Figure 10(a)**.

3.2.4 Scratch hardness

The scratch hardness number for the pearlitic LGI is plotted as a function of progressive applied load in **Figure 11**. The values obtained from measuring the scratch width at different locations of the scratch which correspond to various applied loading conditions and computed using **Eq. (1)**. As can be seen, the scratch hardness decreased as the applied load increased and then remained fairly consistent between 2 GPa and 3 GPa.

Figure 11. Scratch hardness of pearlitic LGI computed based on the data obtained from the scratch width after elastic recovery.

3.2.5 Pearlite deformation mechanism

A large increase of the normal load changed the deformation mechanism of the pearlite from ductile to brittle failure. This change was captured at high magnification in the SEM and images are shown in **Figure 12(a)-(d)**. A closer look at the SEM images shows the scratch behaviour of pearlite matrix, varies under progressive load scratch testing along the scratch track. This could be explained by different mechanical properties and characteristics of the pearlite lamellas structure for instance interlamellar space parameter [36, 37], which gave rise to deform pearlite in different ways. This could be considered as an indication of the bulk mechanical properties. It is also seen that the deformation mechanism, to a large extent, is dependent on the induced normal load and depth of scratching. In addition, as observed, the material removal and debris/chips formation process depends upon the scratch depth. To scrutinise the pearlite scratch response, under very low load of 50 mN, no notable interaction with a very smooth scratch track was detected in the pearlite proven by that the pearlite matrix (ferrite and cementite plates) remained unaffected, as depicted in **Figure 12(a)**. Increasing the scratch load to ~ 500 mN resulted in shearing off the material without much plastic deformation around the indenter as very little formed bulge pile-ups could be distinguished on the scratches' sides, showing the insignificant plastic deformation during scratching.

Figure 12. Scratch deformation behaviour of pearlite structure under progressive load scratching: (a) no significant deformation, (b) onset of the plastic deformation and yielding of pearlite structure, (c) severe plastic deformation of pearlite and debris formation, (d) severely affected matrix, stick-slip occurrences and pile-up formation of pearlite. Scratch direction is from bottom to top.

However, under an applied load of ~ 800 mN, we could detect still a smooth track, however, as presented in **Figure 12(b)**, the onset of plastic deformation of pearlite and perceivable deformed pearlite parallel to the scratching direction are visible. This onset criterion can be identified by the relatively smooth scar grooves and formed as side bulges along the scratch length and some wear debris attached to the bulk. In another word, applying such a high scratch load was found as a threshold load for the current pearlite structure to deform ferrite and cementite plates and induce such a lateral displacement of the pearlite phase.

However, completely different deformation mechanism scenario would control the pearlite deformation behaviour when the scratch load reaches 1500 mN. Increasing the scratch load to such a level resulted in a coarse scratch scar with a substantial displacement of pearlite together with occurrence of slip-stick phenomenon in the bottom of the grooves and formation of sharp shape debris, as shown in **Figure 12(c)**. It is important to note here that these unwanted sharp debris, formed at 1500 mN scratch load and above, are very harmful to the abrasion resistance (particularly in a closed-tribosystem such as a combustion chamber) owing to their potential of secondary damage and scratching during sliding processes [29]. One extreme is the behaviour shown by further increase of scratch load up to 2500 mN and above. This observation can be related to the large compressive stress, which is built around the tip, particularly in front and beneath the indenter. Such a high induced compressive stress, due to the high scratch load, results in a high strain to the material in front of the indenter surface rather than the bulk material.

Under such high scratch load condition, the material in contact with the tip of the indenter experiences a severe plastic deformation and failure both to the matrix and graphite lamellas, which resulted from the high stress in the bulk material. This could also lead to wear debris formation and very coarse and successive delamination of the matrix, as detected in the bottom of the scratch track and shown in **Figure 12(d)**. In this scratch (abrasive wear) mode, the material removal primarily takes place due to the stick-slip events and micro-cutting abrasion mechanism which are the main processes involved in wear debris formation during the present single-pass scratching at higher scratch loads and depths. However, some pile-up can be seen on the sides of the scratch indicating ductile deformation. In addition, the fracture and extrusion of the graphite lamellas from their pockets most likely occurs under such a high loading condition, as one of these cases can be observed in front of the indenter for scratch No. IV at normal loading of 3000 mN (**Figure 6(b)**).

4 Conclusions

Based on the microscratch testing using a sphero-conical diamond indenter, performed under constant and progressive load conditions on a typical LGI sample, the following main conclusions can be drawn:

- i. Increasing the scratch load in a progressive manner and hence scratch depth significantly affected deformation mechanism happening during the scratching process as so increasing the scratch load resulted in increase of both the material removal and sideways pile-ups formation, which matrix deformation occurring became very severe over 1500 mN and above applied load conditions.
- ii. The critical load for the onset of pearlite plastic deformation and the evolution of the pearlite deformation were determined under different scratch load conditions. At low-applied load ~ 500 mN, the micro-ploughing mechanism controlled the plastic deformation of pearlite, while increasing the scratch load up to ~ 1500 mN and above caused to micro-cutting with a significant plastic deformation/displacement of pearlite, debris/chips formation. This scratch mechanism was accompanied with a coarse successive matrix delamination in the bottom of the scratch tracks.
- iii. The matrix deformation in the form of micro-ploughing, micro-wedge formation and micro-cutting had a significant influence on frictional force and friction coefficient values. As the scratch load increased, the frictional coefficient increased and then decreased which is explained by the transition from the ploughing mode to wedge-formation and then cutting mode during scratching.

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6 References

- [1] Sudarshan TS, Bhaduri SB. Wear in cylinder liners. *Wear* 1983;**91**(3):269-279. [https://doi.org/10.1016/0043-1648\(83\)90072-8](https://doi.org/10.1016/0043-1648(83)90072-8).
- [2] Saeed A, Khan ZA, Hadfield M, Davies S. Material characterization and real-time wear evaluation of pistons and cylinder liners of the Tiger 131 military tank. *Tribol Trans* 2013;**56**(4):637-644. <https://dx.doi.org/10.1080/10402004.2013.771416>.
- [3] Sugishita J, Fujiyoshi S. The effect of cast iron graphites on friction and wear performance I: Graphite film formation on grey cast iron surfaces. *Wear* 1981;**66**(2):209-221. [https://doi.org/10.1016/0043-1648\(81\)90115-0](https://doi.org/10.1016/0043-1648(81)90115-0).

- [4] Chandrasekaran S, Khemchandani MV, Sharma JP. Effect of abrasive contaminants on scuffing. *Tribo Int* 1985;**18**(4):219-222. [https://dx.doi.org/10.1016/0301-679X\(85\)90065-9](https://dx.doi.org/10.1016/0301-679X(85)90065-9).
- [5] Ma Y, Zhao W, Li S, Jin Y, Wang Y, Simon TC. Lubricating durability of two GF category engine oils. *Ind Lubr Tribol* 2005;**57**(4):161-167. <https://dx.doi.org/10.1108/00368790510601725>.
- [6] Eyre TS. Wear characteristics of metals. *Tribo Int* 1976;**9**(5):203-212. [https://doi.org/10.1016/0301-679X\(76\)90077-3](https://doi.org/10.1016/0301-679X(76)90077-3).
- [7] Ghasemi R, Elmquist L. The relationship between flake graphite orientation, smearing effect, and closing tendency under abrasive wear conditions. *Wear* 2014;**317**(1–2):153-162. <https://doi.org/10.1016/j.wear.2014.05.015>.
- [8] Cozza RC, Tanaka DK, Souza RM. Friction coefficient and wear mode transition in micro-scale abrasion tests. *Tribo Int* 2011;**44**(12):1878-1889. <https://doi.org/10.1016/j.triboint.2011.08.006>.
- [9] Keller J, Fridrici V, Kapsa PH, Vidaller S, Huard JF. Influence of chemical composition and microstructure of grey cast iron on wear of heavy duty diesel engines cylinder liners. *Wear* 2007;**263**(7–12):1158-1164. <https://doi.org/10.1016/j.wear.2007.01.091>.
- [10] Fessler RR, Fenske GR. Multiyear program plan: Reducing friction and wear in heavy vehicles. NTIS: DE2003771210, 1999.
- [11] Willn JE, Brett PS. Piston ring scuffing during running-in—the influence of lubricants and materials. *Proc Inst Mech Eng* 1977;**191**(1):241-256. <https://doi.org/10.1243/PIME PROC 1977 191 031 02>.
- [12] Neale MJ. Piston ring scuffing—a broad survey of problems and practice. *Proc Inst Mech Eng* 1970;**185**(1):21-32. <https://doi.org/10.1243/PIME PROC 1970 185 008 02>.
- [13] Zabala B, Igartua A, Fernández X, et al. Friction and wear of a piston ring/cylinder liner at the top dead centre: Experimental study and modelling. *Tribo Int* 2017;**106**:23-33. <https://doi.org/10.1016/j.triboint.2016.10.005>.
- [14] Xiang C, Sue HJ, Chu J, Coleman B. Scratch behavior and material property relationship in polymers. *J Polym Sci Part B Polym Phys* 2001;**39**(1):47-59. [https://doi.org/10.1002/1099-0488\(20010101\)39:1<47::AID-POLB50>3.0.CO;2-2](https://doi.org/10.1002/1099-0488(20010101)39:1<47::AID-POLB50>3.0.CO;2-2).
- [15] Riahi AR, Alpas AT. Wear Map for Grey Cast Iron. *Wear* 2003;**255**(1–6):401-409. [https://doi.org/10.1016/S0043-1648\(03\)00100-5](https://doi.org/10.1016/S0043-1648(03)00100-5).
- [16] Andersson P, Tamminen J, Sandström C-E. Piston ring tribology. A literature survey. *VTT Tiedotteita-Research Notes* 2002;**2178**(1).
- [17] Chalker PR, Bull SJ, Rickerby DS. A review of the methods for the evaluation of coating-substrate adhesion. *Mater Sci Eng, A* 1991;**140**:583-592. [https://doi.org/10.1016/0921-5093\(91\)90482-3](https://doi.org/10.1016/0921-5093(91)90482-3).
- [18] Rodrigo A, Ichimura H. Analytical correlation of hardness and scratch adhesion for hard films. *Surf Coat Technol* 2001;**148**(1):8-17. [https://doi.org/10.1016/S0257-8972\(01\)01329-9](https://doi.org/10.1016/S0257-8972(01)01329-9).
- [19] Sinha SK, Lim DB. Effects of normal load on single-pass scratching of polymer surfaces. *Wear* 2006;**260**(7):751-765. <https://doi.org/10.1016/j.wear.2005.04.018>.
- [20] Briscoe B, Delfino A, Pelillo E. Single-pass pendulum scratching of poly (styrene) and poly (methylmethacrylate). *Wear* 1999;**225**:319-328. [https://doi.org/10.1016/S0043-1648\(99\)00051-4](https://doi.org/10.1016/S0043-1648(99)00051-4).
- [21] Barletta M, Tagliaferri V, Gisario A, Venettacci S. Progressive and constant load scratch testing of single- and multi-layered composite coatings. *Tribo Int* 2013;**64**:39-52. <https://dx.doi.org/10.1016/j.triboint.2013.03.002>.
- [22] Franco LA, Sinatora A. Material removal factor (fab): A critical assessment of its role in theoretical and practical approaches to abrasive wear of ductile materials. *Wear* 2017;**382**:51-61. <https://dx.doi.org/10.1016/j.wear.2017.04.006>.

- [23] Do Vale JL, Cortz M, Bertolini VMS, Da Silva CH, Pintaude G. Comparison of scratch resistance of lamellar and compacted graphite irons used in cylinder liners. J Braz Soc Mech Sci & Eng November 26 2016. <https://doi.org/10.1007/s40430-016-0690-8>.
- [24] Akono AT, Ulm FJ. Scratch test model for the determination of fracture toughness. Eng Fract Mech 2011;**78**(2):334-342. <https://doi.org/10.1016/j.engfracmech.2010.09.017>.
- [25] Lin J-S, Zhou Y. Can scratch tests give fracture toughness? Eng Fract Mech 2013;**109**:161-168. <https://dx.doi.org/10.1016/j.engfracmech.2013.06.002>.
- [26] Petit F, Ott C, Cambier F. Multiple scratch tests and surface-related fatigue properties of monolithic ceramics and soda lime glass. J Eur Ceram Soc 2009;**29**(8):1299-1307. <https://doi.org/10.1016/j.jeurceramsoc.2008.09.019>.
- [27] Choi WJ, Lee JH, Weon JI. Effects of photodegradation and thermal ageing on the scratch behavior of uncoated thermoplastic olefin. Tribo Int 2013;**67**:90-97. <https://dx.doi.org/10.1016/j.triboint.2013.07.004>.
- [28] Bull SJ. Failure mode maps in the thin film scratch adhesion test. Tribo Int 1997;**30**(7):491-498. [https://doi.org/10.1016/S0301-679X\(97\)00012-1](https://doi.org/10.1016/S0301-679X(97)00012-1).
- [29] Mendas M, Benayoun S. Investigating the effects of microstructure on the wear mechanisms in lamellar cast irons via microscratch tests. Tribo Int 2013;**67**(0):124-131. <https://dx.doi.org/10.1016/j.triboint.2013.07.009>.
- [30] Ghasemi R, Elmquist L. A study on graphite extrusion phenomenon under the sliding wear response of cast iron using microindentation and microscratch techniques. Wear 2014;**320**(1-2):120-126. <https://dx.doi.org/10.1016/j.wear.2014.09.002>.
- [31] Kataria S, Kumar N, Dash S, Tyagi AK. Deformation of SS 304 LN during Scratch Test and Influence on Evolution of Coefficient of Friction. 2009;**2009**. <http://dx.doi.org/10.1155/2009/648075>.
- [32] Ghasemi R, Elmquist L. Cast iron and the self-lubricating behaviour of graphite under abrasive wear conditions. Paper presented at: SPCI 10, 2014; Mar Del Plata, Argentina.
- [33] Sekler J, Steinmann PA, Hintermann HE. The scratch test: Different critical load determination techniques. Surf Coat Technol 1988;**36**(1):519-529. [https://doi.org/10.1016/0257-8972\(88\)90179-X](https://doi.org/10.1016/0257-8972(88)90179-X).
- [34] Eyre TS. Friction and wear of cast irons. *Metals Handbook: Friction and Wear of Cast Irons, Friction, Lubrication, and Wear Technology*, ASM, Materials Park, Ohio, USA. Vol 18, 10th ed.; 1992:695-701.
- [35] Tomlinson WJ, Dennison G. Effect of phosphide and matrix microstructures on the dry sliding wear of grey cast iron. Tribo Int 1989;**22**(4):259-264. [https://doi.org/10.1016/0301-679X\(89\)90084-4](https://doi.org/10.1016/0301-679X(89)90084-4).
- [36] Modi OP, Deshmukh N, Mondal DP, Jha AK, Yegneswaran AH, Khaira HK. Effect of interlamellar spacing on the mechanical properties of 0.65% C steel. Mater Charact 2001;**46**(5):347-352. [https://doi.org/10.1016/S1044-5803\(00\)00113-3](https://doi.org/10.1016/S1044-5803(00)00113-3).
- [37] Langford G. Deformation of pearlite. Metall Trans A 1977;**8**(6):861-875. <https://doi.org/10.1007/bf02661567>.

Highlights

- Interactions between abrasive particles, pearlite and graphite are simulated.
- Scratch load effects on deformation mechanism of pearlitic matrix is discussed.
- The critical load for the onset of pearlite plastic deformation is determined.