Friction and wear performance of functionally graded ductile iron for brake pads

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Abstract

Due to its wear resistance, functionally graded ductile iron (FGDI) is a potential material for automotive brake pads. In this investigation it was studied (i) under well controlled sliding conditions in a typical tribological model-test to show in detail the mechanism behind improved wear resistance, namely the “property on-demand” functionality in the sub-surface zone and (ii) in a validation experiment on a disc-brake machine that mimic realistic brake-

contact conditions, at various elevated temperatures against a carbon-reinforced ceramic disc in order to understand its tribological behaviour in a real automotive brake application. The results revealed a positive effect of the functional gradient zone (FGZ) on the wear performance of the functionally graded ductile-iron pads. Most notably, improved wear resistance was observed under sliding model-test conditions as well as a more-stable wear and wear that is less sensitive to the contact temperature during a disc-brake test. In addition, the sliding model-tests revealed that FGZ leads to faster running in and a more stable coefficient of friction. The disc-brake tests also show that FGZ ensures a relatively constant coefficient of friction for all contact temperatures. Surface analysis of the pads further revealed that oxidized, smoothened plateaus containing graphite nodules were formed on the pads. On the other hand, a patchy and layered transfer film resulting from the pads was formed on the disc's surface.

Keywords: Functionally graded ductile iron, automotive brake pads, third-body formation.

1. Introduction

The braking system is one of the most crucial parts in all automotive applications requiring controlled friction and wear behaviour. A conventional automotive braking system consists of a disc and brake-lining pads, and must fulfil requirements such as good wear resistance [1-4], a stable coefficient of friction [1-5], reduced noise and a reduced emission of particulate matter [4, 6]. To achieve these requirements, the temperature conditions tailored by the right thermal conductivity [1] and the formation of a friction layer or a third body are often

mentioned as key properties [4, 7] and are thus also in the scope of many recent studies [1-4, 7-12].

In addition to the mechanisms that affect thermal and frictional properties, the main scope of recent studies in the field of braking systems is the development of new formulations for brake pads [4, 13]. There are commonly more than ten different constituents in a pad's material [3, 14, 15] that are also subjected to changes and substitutions due to environmental and legislative demands. These demands have resulted in the removal of asbestos materials [3, 16] and producing pads without asbestos, based on metal-matrix composites [1, 9, 16], polymer-matrix composites [9], organic [4, 7, 10], semi- and low-metallic compounds [2, 13]. What is more, in the next few years, legislation will require the replacement of copper, which is one of the key constituents of pads [17]. This has led to several attempts in the past few years to find proper substitution options [18] and to develop other eco-friendly materials [19]. The main issue in this respect is the fact that a wide range of pad formulations are used in practice [13]. Furthermore, pad formulations are usually based on experience [3, 12, 14, 19], which means systematic improvements and appropriate replacements with novel constituents that will not deteriorate but improve the friction and wear performance. Furthermore, improved wear resistance with the reduced emission of the particulate matter [4] of pads remains one of the challenges for the future development of pad materials.

Ceramic brake discs appeared on the market and were promoted as a sporty, lightweight, very low or zero wear option with much greater frictional power [20, 21]. However, any brake pad with ceramic discs is subject to extreme contact temperatures, rapid deterioration and wearing out. This problem must be solved if ceramic discs are to be adopted in mass-market automotive production.

In this study we present a novel material can could fulfil current demands for brake pads and provide improved wear resistance, making them potentially suitable for ceramic discs, i.e., functionally graded ductile iron (FGDI). Namely, ferrous based functional graded materials have been investigated in various studies [22-25], especially in terms to obtain composites with different phases for specific applications. This study presents, novel ductile iron that is reinforced at the surface by hard carbides formed as a result of the addition of chemically selected inserts (functional gradient zone - FGZ) [26, 27]. Thus, this new material combines high hardness and lubricity through the presence of carbides and carbide nodules, respectively. It is also suitable for pairing with carbon-reinforced ceramic [28] in brake pads.

The innovative mechanism of “in-situ” generation of the hard sub-surface zone via FGZ “on-demand” was studied in a model test at well-controlled sliding conditions that provide severe enough conditions resulting in stress and contact temperature that ensure formation of hard sub-surface zone. In addition, the ultimate verification of the sub-surface hardening mechanisms with tribological performance improvements were further validated in a disc-brake test, mimicking the realistic automotive brake-contacts using the same contact energy input per unit area (energy density) as in automotive brake applications [21].

2. Experimental

2.1. Materials used

The investigated material was functionally graded ductile iron (FGDI) that consists of three regions, i.e., ductile iron with graphite nodules, selected inserts and a functional gradient zone (FGZ) between these two regions (Figure 1). Ductile iron is unalloyed and, in addition to iron, contains mainly C, Si, Mn and Mg (Table 1). The composition of the inserts is presented in

Table 1. The inserts act as reservoirs of Cr and Ni, and in the outer zone also W and B. The chemicals of the insert react with the ductile iron as a source of carbon in order to form hard carbides in the FGZ for high-wear applications at high temperatures. The microstructure of the studied samples is presented in Figure 2. Numerous carbides, different in terms of shape and composition, are formed below the surface of the sample in the FGZ where the wear resistance has to be improved. The length of the FGZ depends locally on the Cr content and was in our case about 3.6 mm. Thus, the FGZ differs from ductile iron because of the presence of carbides and smaller graphite nodules in the matrix [26]. The materials were also heat treated. First, an austenitizing process at 900°C for 60 min, followed by an austempering process at 350°C for 60 min in a salt bath (with 50% of NaNO₂ and 50% of KNO₃) and cooled in air. Details of the material production procedure and the microstructure of the material are described in [26, 27]. The R_a roughness of the produced material was 0.2 µm.

Figure 1: Surface of functionally graded ductile iron made of inserts surrounded by the chemical functional gradient zone (FGZ) and ductile iron.

Table 1: Composition of the functionally graded ductile iron.

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Elements, wt.%	Ductile iron	Inserts (reservoirs)
C	3.7–3.9	not detected
Cr	/	24
Mg	0.03	/
Mn	0.12–0.16	2
Mo	/	/
Ni	26.8×10^{-3}	4.5
Si	2.7–2.8	/
Other trace elements	Cu, P, S, Mo	/
Others	Fe (balance)	Si (trace), Fe (balance)
Selective surface elements	/	W, B

Figure 2: CCr⁻ SIMS images in the FGZ, highlighting the evolution of the microstructure through the distribution of carbides. M stands for Cr, Fe. White contrast represents the highest intensities of CCr⁻, while black contrast represents the lowest ones.

The counter material for the tests on a reciprocating-sliding machine was hardened steel (DIN100Cr6 / AISI52100) cylinder (Φ 10 mm $\times$ 14 mm) with a hardness of 62 HRc and a R_a roughness of 0.05 μm . The steel material was selected to allow good contact aligning and well-controlled contact conditions with the goal of tribological-affecting the FGDI subsurface zone rather than study and affecting the exact surface wear mechanisms. The counter materials used for the brake tests were commercially available, double matrix composite (DMC) brake discs. They were built of SiC and a C-matrix reinforced with C-fibers mats. Namely, the supporting core is made of C/C composite in order to maintain its mechanical properties at elevated temperatures (up to 1400 °C) and is covered with a reaction-bonded SiC layer that is 400 ± 20 μm thick. This surface SiC layer gradually changes with depth from the surface to a mixed layer of C/C and SiC and further to a pure C/C matrix at 550 ± 20 μm below the surface [29]. The roughness of the disc had R_a of 5.20 ± 0.06 μm .

2.2. Tribological sliding tests

For an in-depth understanding of the FGDI behaviour under well-controlled tribological conditions, a tribological test was made on a reciprocating sliding machine (TE-77, Cameron-Plint Ltd., England). The reciprocating sliding tester was selected in order to create severe enough contact conditions to ensure “in-situ” and “on demand” sub-surface modification due to contact stresses and contact temperature generated through frictional heating, thus allowing systematic study of material modification in the near-surface and sub-surface regions.

The tribotester consists of a stationary base, a holder (which is driven in a linear oscillating motion), a loading cell and a computer-based regulation system. The lower flat samples (FGDI) were fixed in the base, while the upper specimens, i.e., hardened steel cylinders, were fixed in the oscillating holder, Figure 3. In all the experiments, 50 N of normal load was applied through the loading system, corresponding to a maximum contact pressure of 160 MPa. A sliding stroke of 8.8 mm and an oscillating frequency of 5.7 Hz were used, resulting in a average sliding velocity of 0.1 m/s. In each test, the total sliding distance was 100 m. The tests were performed at room temperature ($T=21\pm1^{\circ}\text{C}$). The frictional force was monitored throughout the test with a load transducer, and was digitally recorded. The average coefficient of friction was determined for sliding distances of 80 m and 100 m, after reaching a steady-state value.

Figure 3: Schematic representation of the contact during the reciprocating-sliding experiment.

Due to the fact that the hard carbides are formed as a gradient around the inserts, the highest hardness is expected below the surface in the FGZ (see hardness profile in Figure 4, 1st step). Accordingly, the effect of the hardness in the FGZ on the tribological performance of the FGDI was investigated by performing two different tests. In first step, the tribological test was made on the original surface of the sample (Figure 4, 1st step). After the first phase, the top surface with the wear trace was removed by mild polishing and flattening of the sample. During this mechanical process, a thickness of 0.07 mm was removed to reach the subsurface region near the inserts with higher hardness. Then, the second step of the tribological test was performed on the thinned sample (Figure 4, 2nd step) where the surface had a much higher hardness. For each material and each step (1st and 2nd) the tribological test was performed four times and a statistical evaluation of the results (steady-state coefficient of friction and wear) was conducted.

Figure 4: Schematic representation of the two-step reciprocating-sliding tests.

The wear of the investigated FGDI samples for both testing steps was determined at the end of each tribological test by using a gravimetric technique. The wear traces were additionally evaluated using a 3D optical microscope with white-light interferometry (Contour GT-K0, Bruker, France).

2.3. Tests on a disc-brake machine

The second part of the tribological investigation was made on a reduced-scale, disc-brake test rig that can measure the coefficient of friction under operating conditions (i.e., sliding speed, contact pressure, temperature) that are close to those in real braking applications [21]. This test was used to verify the sub-surface “in situ” and “on demand” hardening mechanisms in contact conditions mimicking the real automotive brake-contact conditions, where the same energy input per unit area (energy density) as in automotive brake applications is introduced.

Figure 5: Schematic representation of the brake test rig (head) with contact disc-pads (adapted from [21]).

The test rig consists of a rotating brake disc and two stationary brake pads (Figure 5). The pads were made of FGDI. The rotation speed of the disc was 6000 rpm, corresponding to a sliding speed of 14.45 m/s. A normal load of 100N (0.4 MPa) was applied to the pads through a specially designed pneumatic system that was controlled by the contact temperature. The selected contact pressure of 0.4 MPa and sliding speed that corresponds to a car speed of 120 km/h represent valid contact conditions that are obtained in real automotive braking systems [21].

The contact temperature was measured by using thermocouples (Figure 5) that were installed in the pads just below the contact zone, with an initial distance to the pad-disc interface of 0.7

mm (Figure 6). During the tests the coefficient of friction was monitored continuously.

Details about brake test rig used are reported elsewhere [21].

Figure 6: Initial position of the thermocouple within the pad and relative to the pad-disc interface during the tests on the disc-brake machine (adapted from [21]).

The tests consist of loading and re-loading braking cycles. Each braking cycle lasts until a pre-set braking temperature is reached and so depends on this pre-set temperature. The time between the loading and re-loading braking cycles is used to cool the system and lasts until the measured temperature decreases for 5°C below the pre-set braking temperature. Afterwards, the new braking cycles starts.

The tests were divided into five parts. The first part of the test was running-in, carried out at a temperature of 250°C, where 30 braking cycles were used to provide completely parallel pads and disc. After this running-in, regular higher-temperature tests were made at 300°C, 400°C, 500°C and 600°C. Selected temperatures were in the range of temperatures that can be achieved, for this pad-disc combination, in real automotive brake applications [21]. For each of these four temperatures, five braking cycles were performed. All these five steps together form a ‘test cycle’ (see table 2).

Table 2: ‘Test cycle’ consisting of five steps with different numbers of ‘braking cycles’.

Step	Temperature	Number of braking cycles
1 (running-in)	250°C	30
2	300°C	5
3	400°C	5
4	500°C	5
5	600°C	5

In addition to the continuous monitoring of the coefficient of friction during the entire test, for each step we also determined:

- i. The sliding distance that represents the total sliding distance to complete five cycles at each step (i.e., temperature), Table 2.
- ii. The thickness of the linear wear of a pad that corresponds to the difference between the thicknesses of the pad samples before and after each step and shows the penetration depth, Figure 7.
- iii. The normalized weight loss that represents the pad’s and the disc’s weight loss within each step, normalized with the total sliding distance within this step.

For each pad-disc combination, successive test cycles were performed (table 2) until the surface penetration reached a value close to 0.7 mm beneath the unworn surface (Figure 6 and Figure 7), which represents the depth at which it is likely to reach the thermocouple. A different thickness between the surface and the thermocouple affects the measured temperature. However, earlier studies [8, 20, 21] have shown that after a typical number of cycles at each step, the representative average temperature within each step is very well captured and well describes the temperature differences during these tests.

Figure 7: Evolution of the distance pad surface / thermocouple during the test on disc-brake machine: (a) before tests (unworn pad), the distance is 0.7 mm and (b) during test (worn pad), the distance is reduced.

3. Results

3.1. Reciprocating-sliding tests

The evolution of the coefficient of friction during the sliding tests is presented in Figure 8. Two different tests were performed: for the FGDI samples with the original thickness (1st step, Figure 8a) and after the removal of 0.07 mm of thickness (2nd step, Figure 8b). All four repetitions for each test are shown in Figure 8. It is clear that when using the samples with the original thickness (Figure 8a) the evolution of the coefficient of friction varies between different repetitions of the test. Moreover, the running-in is relatively long, with the coefficient of friction reaching a steady-state value after 75 m of sliding distance or even later. Another important observation is that the values of the steady-state coefficient of friction differ from 0.52 up to 0.63. On the other hand, in the 2nd step (when 0.07 mm of material thickness was removed to reach the inner part of the FGZ), the coefficient of friction reaches the steady-state more quickly, after between 25 m and 50 m of sliding distance (Figure 8b). The repeatability of the coefficient of friction in steady-state conditions is very good.

Figure 8: Evolution of the coefficient of friction during sliding tests in (a) 1st step and (b) 2nd step.

The steady-state coefficients of friction and the wear rates of the tested FGDI are summarized in Figure 9. It can be observed that the coefficient of friction is slightly lower in the 2nd step (after the removal of 0.07 mm of thickness), but still high enough (around 0.5) for brake applications. In the 2nd step we see that there is a lower standard error for the steady-state coefficient of friction, indicating better repeatability of the results and a more stable coefficient of friction. When using samples with the thickness (1st step), it is clear that the wear rate is about $0.31 \cdot 10^{-4} \text{ mm}^3/\text{Nm}$. However, in the 2nd step, the wear was not detectable anymore with the gravimetric technique, indicating a drastically improved wear resistance.

Figure 9: (a) Steady-state coefficient of friction and (b) wear rate of investigated FGDI material (for original and after removal of 0.07 mm of thickness) tested against steel cylinder.

Since the wear in the 2nd step was undetectable using the gravimetric technique, additional analyses of the wear traces were made. In Figure 10a the edges of the wear traces are shown using optical microscopy. The same transitional area was also examined with 3D optical microscopy using white-light interferometry (WLI) (Figure 10b) and profiles in the x (Figure 10c) and y directions (Figure 10d). All these images and profiles confirm the very low or even negligible wear for the inner part of the FGDI material.

Figure 10: Edge of the wear trace observed by: (a) optical microscopy and (b) 3D optical microscopy using white-light interferometry, with surface profile at the transition from unworn surface to wear trace in (c) x-direction and (d) y-direction.

3.2. Tests on disc-brake machine

Coefficient of friction

The coefficient-of-friction data from the disc-brake machine are summarized in Figure 11. The average value of the coefficient of friction is around 0.5, and ranges from 0.45 to 0.54, depending on the test cycle and the contact temperature. However, these differences in the coefficient of friction are statistically not significant and fall within the measurement uncertainty.

Figure 11: Coefficient of friction for all the tested contact temperatures and cycles during the disc-brake test.

Wear of the pad (linear wear)

The evolution of the removed thickness of the pads, i.e., the wear depth (linear pad wear), during the disc-brake test is shown in Figure 12. It is clear that we were able to perform four test cycles until the wear depth reached a value of 0.6 mm (i.e., the position 0.1 mm from the thermocouple). The results also show that the wear depth decreases with every additional test cycle, confirming the nature of the functionally gradient material where the hardness varies accordingly. Namely, the wear is the highest in the first two testing cycles (around 0.20 mm), while in the following two cycles it is significantly lower (0.11 and 0.08 mm) and thus in agreement with a steeper hardness gradient below the surface.

Figure 12: Evolution of the removed thickness of the pad (surface penetration) during the disc-brake test, revealing the properties of the functional gradient zone with increased wear resistance getting closer to the inserts. At the beginning of the test, the thermocouple is at a distance of 0.7 mm from the unworn surface of the pads.

Wear of pads (weight loss)

The wear evaluated from the weight loss of the pads and normalised by the sliding distance is reported in Figure 13 for all the temperatures within each ‘test cycle’. In general, the average normalized weight loss is the lowest in the 4th (last) cycle (i.e. $9.5 \cdot 10^{-5}$ g/m). However due to the high standard errors in the first three cycles, this difference is not statistically significant for most of data, when evaluated with Student T-test. However, for results at 600 °C, which is probably the most relevant temperature for these materials, Student T-test shows even highly significant difference between the 4th cycle with the previous two cycles (p values of 0.0181 and 0.0150).

Nevertheless, for a wear depth up to 0.5 mm we can observe large deviations in the weight loss for a certain temperature, indicating that temperature plays an important role in the wear properties of the pads. However, when the wear depth exceeds 0.5 mm, reaching the hardest phase of the FGZ, the weight loss is relatively uniform for all temperatures, with small deviations, and stabilizes at around $1.0 \cdot 10^{-4}$ g/m.

Figure 13: Wear of the pads as a function of the surface penetration at the tested contact temperatures for all four testing cycles.

Analyses of the pads and disc using scanning electron microscopy (SEM)

After the tests on the disc-brake machine, the pads and disc were analysed with SEM and WLI in order to determine the formation of the third body that crucially defines the friction and wear performance. The SEM image of the pads in Figure 14 shows the formation of the smoothened plateaus with some scratches in sliding direction and intermediate areas with

torn-off material. Graphite nodules are still visible in these oxidised areas with smoothened plateaus (EDX analysis, Figure 15).

Figure 14: (a) SEM images of FGDI pads with smoothened plateaus and areas with torn-off material. (b) SEM images of smoothened plateaus of FGDI pads with EDX mapping

Figure 15: SEM images of smoothed plateaus of functionally graded ductile-iron pads with EDX mapping.

The disc surface in Figure 16 shows that a patchy and layered film was formed, and on some places abrasively removed. The EDX analyses (Figure 17) show that a transfer film from the pad material was formed on the disc's surface during braking. In contrast, the area without the transfer film consists of some wear debris from pads that can be found due to the abrasive removal of the transfer film.

Figure 16: Transfer film on the carbon-reinforced ceramic disc.

Figure 17: SEM image of the carbon-reinforced ceramic disc with EDX spectrum of transfer film and wear debris.

Discussion

Two aspects of the FGDI need to be highlighted in terms of their use for brake pads, i.e., (i) the effect of the FGZ on the friction and wear performance and (ii) the formation of the third body.

3.3. Effect of FGZ on the friction and wear performance

The FGZ positively affects the friction performance, since for reciprocating-sliding conditions, when a certain thickness of material was removed and the FGZ was reached, the coefficient of friction became more stable, with faster running-in and better repeatability (compare Figure 8b with Figure 8a). What is more, the coefficient-of-friction variation is not significant when the FGZ is reached, while before it was very pronounced – see Figure 9. Further tests on the disc-brake machine also confirmed that the FGZ improves the coefficient-of-friction behaviour. Namely, the coefficient of friction does not show any trend of increasing or decreasing with an increase of the testing cycles with FGZ being in the function – see Figure 11. Furthermore, the results in Figure 11 also confirmed stable values for the coefficient of friction for all the contact temperatures. According to these observations we can conclude that the FGZ improves the friction performance of the FGDI pads and provides a stable coefficient of friction for all the contact temperatures (Figure 11), which is one of the key requirements pad-disc braking system [1-5].

On the other hand, the effect of the FGZ on the wear resistance of the FGDI pads is even more pronounced. Namely, both the reciprocating-sliding (Figure 9) and the disc-brake tests (Figure 13) revealed the improved wear resistance of the pads when the FGZ was reached. As shown in Figure 4, the FGZ provides greater hardness due to the gradually increased

formation of the hard carbides [26], and for the reciprocating-sliding test it was shown that reaching the FGZ results in an improved wear resistance, resulting in undetectable wear (compare the wear results of the 2nd step with the 1st step in Figure 9). The same behaviour was also observed for the disc-brake test. During this test, the wear vs. surface-penetration plot (Figure 13) shows that the wear is strongly affected by the temperature for surface depths up to 0.5 mm, where a lower hardness is expected, whereas the temperature has no effect on wear deeper in the material (beyond 0.5 mm, i.e., when the FGZ with a higher hardness is reached). This means that the FGZ with its gradient composition prevails over the effect of the temperature and determines the improved wear performance. Current ongoing analysis show that this wear performance is further enhanced by the transformation of ausferrite into martensite induced by strain during the wear tests under real braking conditions. Since improved wear resistance is always in the scope of brake-applications studies [1-4], it can be concluded that the FGZ investigated here, with its positive effect on wear resistance, is a potentially new and highly promising solution for metal-matrix-composite brake pads.

3.4. Formation of the third body (friction layer)

The formation of the third body (i.e., the friction layer) is one of the key pad-disc system requirements [4, 7] and the subject of much research [1-3, 7, 9, 10, 12]. For our disc-pad system the third body results from compacted and oxidised wear debris spread on the pads (Figures 14 and 15) and disc (Figures 16 and 17). Namely, as shown in Figure 14, the smoothened plateaus with intermediate areas exhibiting torn-off material were formed on the FGDI pads. The EDX mapping of the smoothened plateaus in Figure 15 revealed the clear presence of oxygen, which was expected due to the high temperatures during the test. The

observed transfer film is also in agreement with other studies, claiming that third-body (friction) layer formation is the result of tribo-oxidation of the metallic surfaces and compacting the debris during attrition [2, 7]. These contact plateaus can rise up to few micrometres above the surface [10]. The graphite nodules present in the ductile iron and the FGZ act as reservoirs of graphite, which is known to be a solid lubricant. According to [7], graphite also determines the composition of the third body (friction films) on the disc and the pads.

The SEM observation of the DMC disc surface reveals patchy, non-uniform and layered third-body film formation (Figure 16). The presence of Cr and Fe on the surface of the worn DMC disc (Figure 16, site 1) indicates the transfer of material from the pads surface. The inserts (Chemical reservoirs) were not affected during the wear tests (they are found deeper in material), while the presence of Cr and Fe suggests that the carbides formed in the FGZ were worn. The EDX analyses revealed that third body (friction) layers originate from the pads as a transfer film. In addition to the transfer-film formation on the disc, the wear-debris particles from the pads were also entrapped around the carbon fibres of the disc (Figure 17, site 2). These observations are in agreement with other studies that reported that friction layers formed on a non- or semi-metallic body (commonly the disc, but in our case the pads) are discontinuous, comprising the primary and secondary plateaus, where the main constituent part for the secondary plateaus is iron oxide [4, 7, 10].

4. Conclusions

Functionally graded ductile iron used for brake pads was tested on well-controlled model sliding test and disc-brake machine. The results obtained in tribological sliding tests revealed that the sub-surface “in-situ” modification of FGZ improved the wear resistance and the results on disc-brake machine indicate that the material is a real candidate for automotive brake pads.

1. The sliding model-test revealed that better wear resistance and a more stable coefficient of friction were achieved when the functional gradient zone with a high hardness was reached (i.e., after a certain amount of top surface material thickness was removed).
2. The reduced-scale brake tests additionally showed similar wear behaviour to the reciprocating-sliding tests. Namely, after the removal of the top surface of the pad and reaching the FGZ with high hardness, the wear became stable and less sensitive to the contact temperature.
3. Functionally graded ductile iron pads with FGZ provided a stable coefficient of friction of 0.5 during the entire brake test and for all the contact temperatures.
4. Third-body film formation occurred on the functionally graded ductile-iron pads and the carbon-reinforced ceramic disc. On the pads, smoothened plateaus including graphite (solid lubricant) nodules were formed, while on the carbon-reinforced ceramic disc a patchy and layered transfer film from the counter pad's surface was formed.

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