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Wear mechanisms of WC-Co drill bit inserts against alumina counterface under dry friction: Part 2 — Graded WC-Co inserts

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Boride phase
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A B S T R A C T

The tribological behaviour of innovative graded cemented carbide inserts were studied by using a rotary tribometer and abrasive alumina counterfaces. This work completes the study made on commercial inserts with homogeneous cobalt content. Inserts with three types of graduation processes were considered: inserts with borides WCoB phases, imbibed inserts and inserts combining both processes (i.e. inserts with reactive imbibition). Physicochemical and mechanical measurements show that the WCoB phases increase the hardness towards the active surface and the imbibition increases the insert core fracture toughness. The wear tests indicate that the boride phases lower the friction coefficient. In addition, as for the commercial inserts, cemented carbide volumes with higher cobalt content also reduce the friction coefficient. Concerning the wear results, the boride phases improve the abrasion resistance. By applying a third body approach, the WCoB phases limit the introduction of cobalt binder in the source flow, the cohesion of alumina particles in the internal flow and the formation of an abrasive paste in the contact. The imbibition process, where the cobalt migration is controlled, does not affect the wear resistance by avoiding a cobalt enrichment of the cemented carbide near the active surface.

Introduction

The cost of a drill bit represents 1% to 10% of the daily drilling investment. Nevertheless, the expenses generated by the tools damage have a great effect on the operating cost. The damages reduce the feed rate which is directly linked to a drop of profitability. Furthermore, the replacement of a tool resulting from critical damages often implies several days of handling. The drilling standby also causes economic losses.

The repeated shocks endured by the roller cone bits mainly produce inserts breakage. Otherwise, with the rotary drilling excavation, the WC-Co inserts abrasive wear is a non negligible component of the overall tool damage. Therefore, one of the manufacturer's challenges focuses on the cemented carbides optimization to jointly improve the insert impact resistance and their wear resistance. Despite the cemented carbide modulation capabilities by changing their cobalt content or their grain size distribution, the WC-Co inserts always suffer from the compromise between hardness and fracture toughness. In one hand, commercial inserts with low cobalt content or small WC grains size are used for their high abrasion resistance. In the other hand, inserts with high cobalt content or high WC grains size have a high impact resistance. Hence, inserts with polymodal grain size distributions are manufactured to balance the physical and mechanical properties of the inserts. Eventually, another way to balance these properties is to act on the insert cobalt distribution. However, the cemented carbides cobalt graduation is a more complex way to optimize the insert properties.

Actually, the graduation processes could improve the insert impact resistance and fatigue resistance by increasing their core cobalt content [1]. They could also enhance the inserts wear resistance by hardening their active surface [2]. In this way, this paper focuses on the tribological behaviour of three different graduation processes: the reactive coating, the imbibition and the reactive imbibition. These processes were performed on the basis of the P8, P12 and P16 commercial inserts (i. e. sintered with respectively 8 wt.%, 12 wt.% and 16 wt.% of cobalt) studied in the part 1.

Various processes can be used to manufacture graded cemented carbides [3]. However, except for the multilayer methods, most of these processes generate a limited gradient in cemented carbide. The imbibition process can realize a cobalt enrichment in the insert core over several millimeters without affecting the cobalt content near the active surface. After sintering, the insert is put on a metal matrix composite compact with an eutectic composition (i.e. WC-Co with 65 wt.% of cobalt referenced Co65) [4]. After the eutectic temperature ($T > [1280]^{\circ}C$), the metal matrix composite melts and the liquid rich in cobalt is then introduced in the insert by migration from the bottom to the

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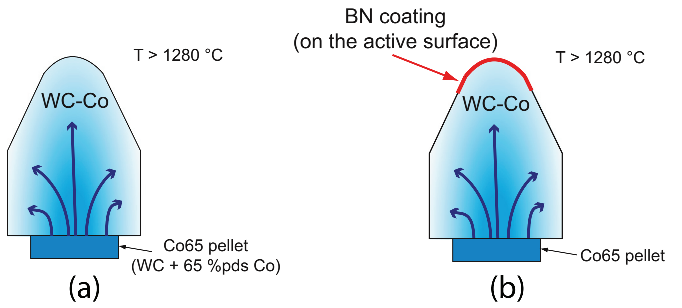

Fig. 1. Liquid cobalt migration from a cemented carbide pellet during imbibition over the eutectic temperature (from [12]): a — imbibition; b — reactive imbibition.

core [5]. The interfacial energy reduction of the system WC-Co is at the origin of the imbibition phenomenon [6]. Obviously, this process increases the insert core ductility and should also increase their impact resistance.

The formation of borides WCoB by boriding processes is described in the literature to improve the wear resistance of carbide tools [7]. Pennington [8] presents the formation of quaternary phases W–B–C–Co by the sintering of WC-Co cemented carbides with materials containing boron (e.g. boron nitride or pure boron). He shows that the boron elements can diffuse in the cemented carbide over several millimeters. Later, Knox and Pennington [9] present a similar process by sintering cemented carbides coated with a material containing boron. According to these authors, this process improves the hardness of the WC-Co and could increase the WC-Co fracture toughness. Likewise, the reactive coating process is initiated by the deposition of boron nitride BN on a sintered WC-Co insert [10]. After this coating deposition, the insert is heated above the binder phase solidus temperature. During the reactive coating process, the bore element diffuses in the cobalt liquid phase, which also contains W and C elements, to form WCoB ternary borides after saturation. The WCoB borides are then formed at the expense of the cobalt phase. The borides are harder than the WC and the core of the WC-Co inserts.

The reactive imbibition combines the reactive coating process to enhance the active surface hardness and the imbibition to increase the insert impact resistance [11].

This work deals with the study of graded WC-Co wear. As in part 1, experiments were carried out using a rotary tribometer. Physicochemical and mechanical properties were also considered to understand the innovative insert wear. Finally, the third body approach exposed in part 1 is introduced again to establish the graded cemented carbide wear mechanism.

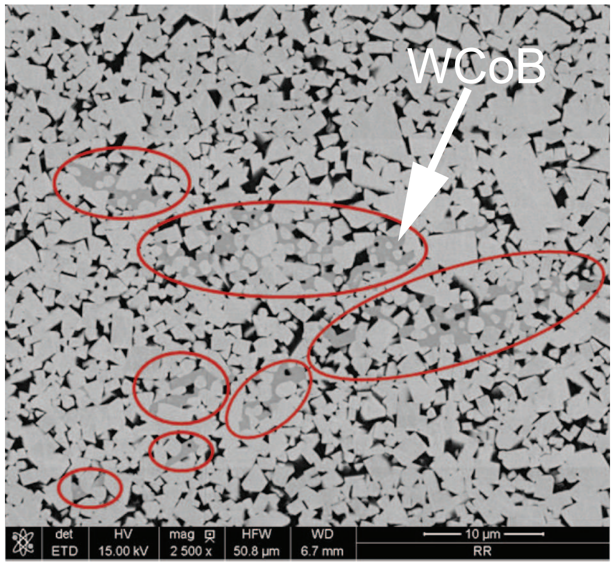

Fig. 3. SEM observation of borides in the microstructure of cemented carbides manufactured with a reactive coating process (with the cobalt phase in black, the WC grains in light grey and the borides in dark grey).

Material properties

Manufacturing processes

The graduation treatments were carried out at the Armines Material laboratory on the basis of the P8, P12 and P16 commercial inserts analysed in part 1:

- An imbibition process was carried out on the basis of the P8 insert and referenced as P8-I (Fig. 1a);
- A reactive coating process was performed at different sintering temperatures and sintering times on the basis of the P12 insert. The graded inserts were then referenced as P12-RC1 and P12-RC2. With the P12-RC2 insert, sintered at a higher temperature and time than the P12-RC1, deeper boride formation and free cobalt depletion from the active surface towards the core are expected;
- A partial reactive imbibition (i.e. only coated on the insert active surface) was performed on the basis of the P8, P12 and P16 inserts and referenced as P8-RI, P12-RI and P16-RI (Fig. 1b). The P16-RI insert was sintered at lower conditions to avoid an excessive migration of cobalt phase in an insert already rich in cobalt.

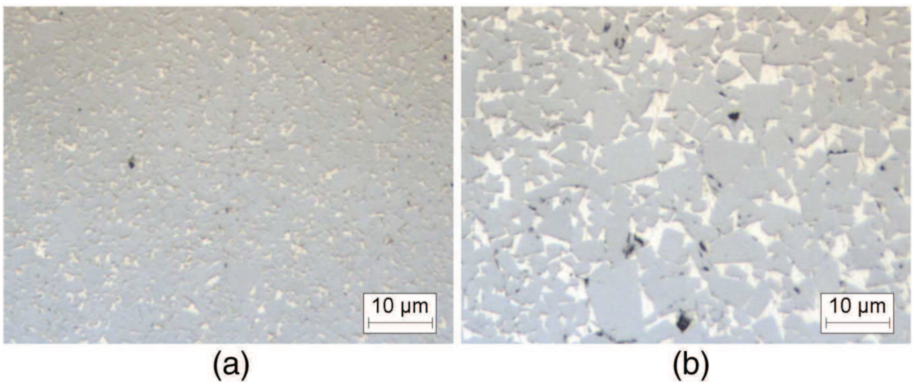

Fig. 2. Optical microscope observations of graded inserts microstructure: a — P8-RI; b — P12-RI.

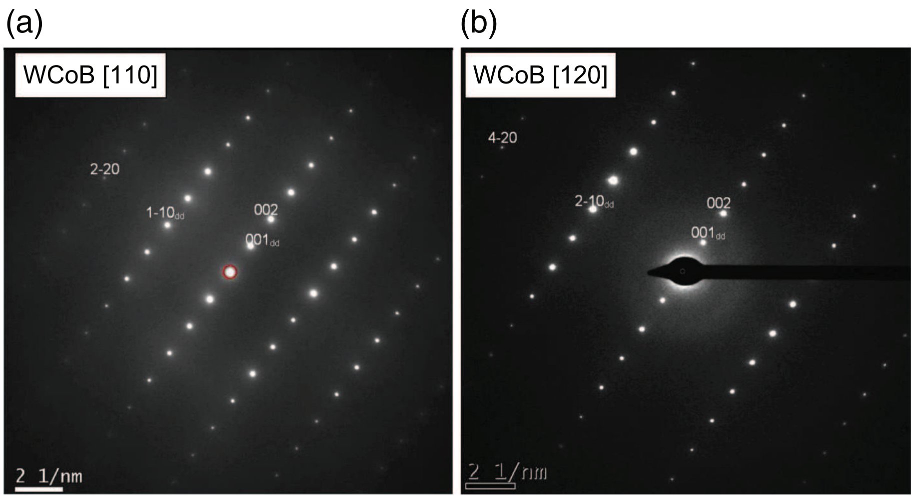

Fig. 4. TEM electron diffraction patterns of the WCoB phase: a — diffraction on [110]; b — diffraction on [120] [13].

Microstructural characterization

The graduation processes do not change the grain size distribution already observed for the commercial inserts P8, P12 and P16 (part 1). For example, the P8-RI exhibits the fine granulometry of the insert P8 (Fig. 2a). The P12-RI insert has the bimodal distribution of the insert P12 with coarse WC grains (Fig. 2b).

Concerning the coated inserts (P8-RI, P12-RI, P16-RI, P12-RC1 and P12-RC2), SEM observations reveal the boride formation in the WC-Co microstructure (Fig. 3). These observations show that the boride phase is finely dispersed in the cemented carbides. The size of this phase can be ranged between few microns and tens of microns. The WCoB phase grows at the expense of the cobalt phase and induces a rounding of the WC grains [11].

In a previous study, diffraction patterns realized during TEM observations were performed to confirm the formation of borides (Fig. 4) [13]. These patterns indicate that the boride phase is a ternary orthorhombic compound. This orthorhombic WCoB is known to enhance the wear resistance of carbide alloys in metal cutting due to its high hardness ([45]*GPa*) [14].

Physicochemical and mechanical properties

The mean cobalt contents p_{Co} of the graded inserts were evaluated from their densities ρ and by correlation with the values obtained with the P8, P12 and P16 commercial inserts using a mixture law (Table 1). The graded insert cobalt contents show that the imbibition process generates a binder phase enrichment of 4wt. % with regard to the commercial inserts. The mean WC grain size $Ø_{WC}$ is slightly modified compared to the commercial inserts. The sintering temperatures and time changes also affect the WC grain size (e.g. P12-RC1 and P12-RC2 inserts). The density ρ, the Young modulus E and the hardness H depend on the cobalt content p_{Co}. Indeed, these parameters decrease with the cobalt enrichment realized by imbibition. Moreover, the hardness decreases from the surface to the core of the graded inserts, explaining the values of discrepancy. All the graded inserts, even the simply coated inserts, have a greater fracture toughness K_{IC} than the associated commercial inserts. One reason of this enhancement is the optimization of the sintering program. For example, the P12-RC2 insert has a fracture toughness 39 % higher than the P12 base insert. Of course, the other main reason is brought by the imbibition process with the P8-I insert fracture toughness representing the double of the one of the P8 insert.

Regarding to the measured physicochemical properties, the graduation processes realize the expected cobalt distribution in the inserts. The insert core is richer in cobalt than the cemented carbide volume near the active surface. As a result, the graded inserts are harder near their active surface and tougher towards their core. That is why only the imbibition of the hardest base insert (i.e. P8) is studied here. The P12 base insert only treated by reactive coating is also interesting because of its good wear resistance observed in the short term but decreasing at the longer term. Finally, all the inserts were treated by reactive imbibition.

Table 1
Physicochemical and mechanical properties of graded inserts.

Inserts	p_{Co} (wt.%)	$Ø_{WC}$ (µm)	ρ (g cm^{-3})	E (GPa)	H (HV 2 kg/10 s)	K_{IC} (MPa·m$^{1/2}$)
P8-I	12 ± 4	3 ± 1	14.4 ± 0.1	513 ± 10	1189 ± 143	22.3 ± 2.1
P8-RI	12 ± 4	3 ± 1	14.4 ± 0.1	476 ± 10	1332 ± 88	17.4 ± 0.9
P12-RC1	14 ± 2	6 ± 3	14.2 ± 0.1	503 ± 10	1063 ± 20	25.6 ± 0.7
P12-RC2	13 ± 1	5 ± 2	14.3 ± 0.1	547 ± 10	1094 ± 37	27.1 ± 0.3
P12-RI	16 ± 4	5 ± 2	14.0 ± 0.1	411 ± 10	1027 ± 30	21.1 ± 1.4
P16-RI	17 ± 3	4 ± 2	13.9 ± 0.2	393 ± 10	982 ± 53	22.7 ± 0.4

Experimental device

As in part 1, the experimental device is a rotary tribometer where a lever arm applies the normal load to a sphere/plane configuration (i.e. spherical tip insert against flat alumina counterfaces). The static insert slides against a rotating alumina counterface at a nominal velocity of 0.5m · s^{-1} and a nominal load of 264N for 1 h. These conditions generate significant wear volumes on the studied inserts. Three experiments were performed on each graded insert.

Torque sensors measured the transverse friction force and a vertical displacement sensor provided changes in wear volume during tests. A speed camera up to 120 frames per second was set to follow the contact dynamics. This speed camera also permitted to confirm the wear volume evolution measured with the vertical displacement sensor.

Friction and wear results

Reactive coating

The mean friction coefficient μ of the P12 commercial insert lay between the two coated insert coefficients (Fig. 5a). The P12-RC2 insert gives significantly the lower friction coefficient. More precisely, as

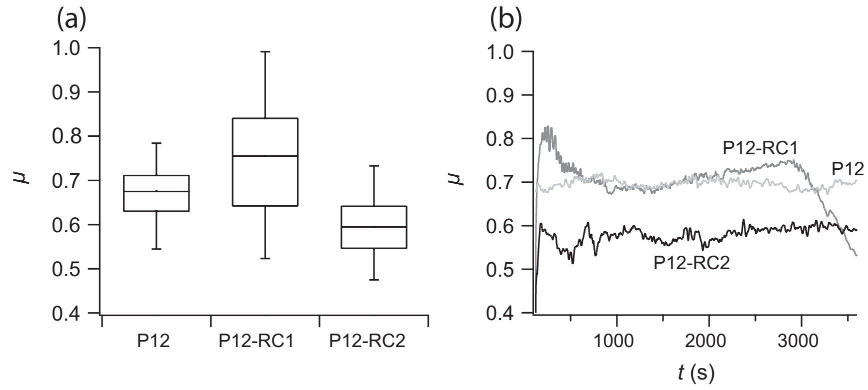

Fig. 5. Coated inserts friction coefficients compared to the reference P12 insert: a — box and whiskers chart with repeatability tests consideration; b — friction coefficients evolution (RMS signals).

seen with the commercial inserts, increasing the hardness or decreasing the cobalt content of the cemented carbides implies an increase of the friction coefficient. In this way, the drop in friction coefficient of the P12-RC1 insert after 3100 ± 100s becomes understandable (with repeatability tests consideration): this observation corresponds to the transition from the WC-Co containing boride phases to a zone richer in cobalt phase during wear (Fig. 5b). This transition occurs at a wear height of 690 ± 160µm on the insert P12-RC1. Because of a deeper boride phase formation, the insert P12-RC2 has not reach this transition at its final wear height of 417 ± 1µm.

As expected, coated inserts wear is lower than the associated commercial base (Fig. 6). The P12 insert wear kinetic is not maintained for the coated inserts.

The P12-RC1 insert displays a first increase of wear volume V_h with a wear rate of $3.1 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$ ($\pm 0.5 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$). Then, a tendency change occurs around 1800s (or 240N · m) with a wear rate of $4.3 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$. Finally, around the friction transition previously observed at 3100 ± 100s, another change appears with a new wear rate of $12.5 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$. This value is similar to the P12 insert wear rate of $12.1 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$ observed before 1800s.

The insert P12-RC2 wear volume has a logarithmic trend, similar to the P12 insert wear volume and partially similar to the P12-RC1 insert one. Therefore, two transitions between the WC-Co with borides and the WC-Co without boride occur on the insert P12-RC1 wear kinetic. The first one should be related to the graded insert wear across the boundary between the WC-Co with WCoB and the WC-Co core and the mixed friction between these two materials. This boundary is never reached for the insert P12-RC2 during the tests. The last transition must be due to wear mechanisms only realized in the base cemented carbide richer in cobalt binder and equivalent to the P12 insert composition.

The ratio of the alumina final worn volume W_f over the insert final worn volume V_f informs on the relative wear of the counterface (Fig. 7). When this ratio is greater than one, the alumina counterface has simply a greater wear volume than the associated insert. According to the ratio, the alumina counterfaces have a greater wear than the P12, P12-RC1 and P12-RC2 inserts. The counterfaces have an equivalent wear behaviour towards the insert P12 and the insert P12-RC1. With the P12-RC2 insert, the alumina counterface wears twice more than the two other inserts.

Imbibition

The P8-I imbibed insert has a gradual cobalt content with an average at 12 ± 4wt. % similar to the one of the P12 insert. Near the active surface, this insert reaches the P8 insert cobalt content (i.e. around 8wt. %). This composition is reflected in the friction coefficient results. Indeed, the mean friction coefficient μ of the insert P8-I has an intermediate value ranged between the P8 insert and the P12 insert (Fig. 8a). The P8-I friction coefficient decrease during the wear experiments can be explained by the progressive participation of the cobalt phase in the sliding contact (Fig. 8b).

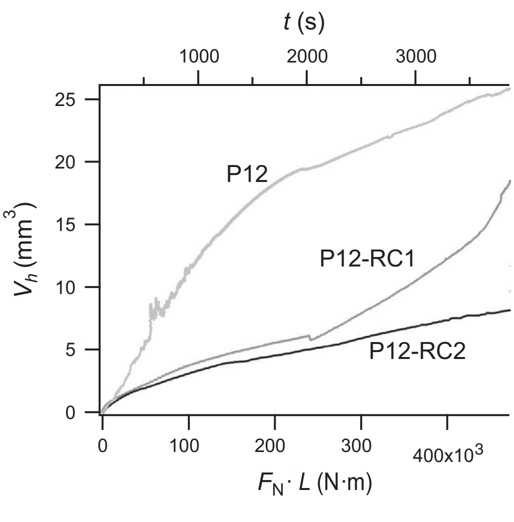

Fig. 6. Wear during experiments with the P12 commercial insert and the coated inserts: inserts wear volume V_h vs. time and the product load F_N by sliding distance L.

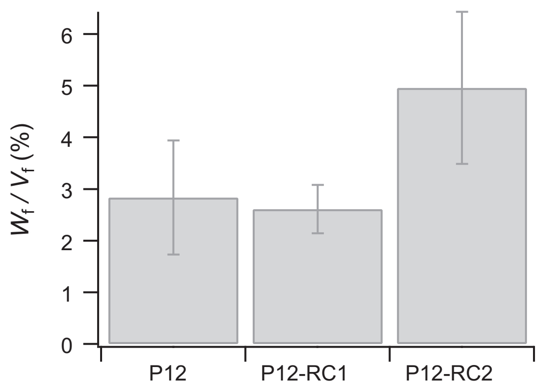

Fig. 7. Ratio of the alumina final worn volume W_f and the inserts final worn volume V_f.

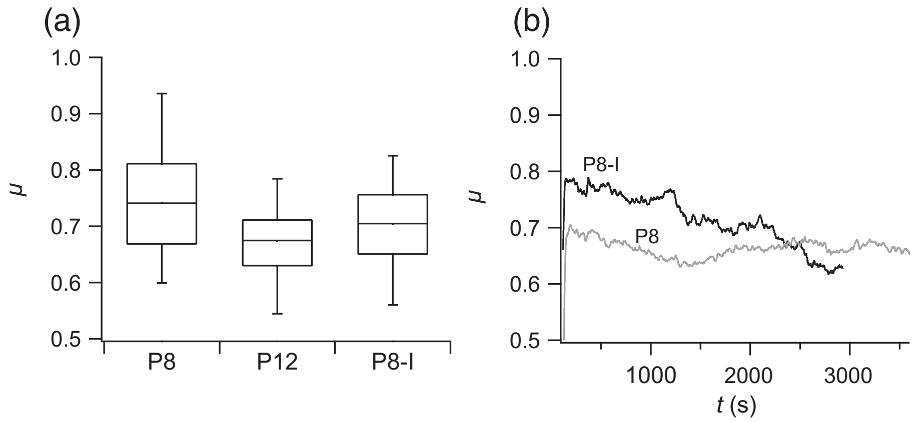

Fig. 8. Imbibed inserts friction coefficients compared to the reference insert P8: a — box and whiskers chart with repeatability tests consideration; b — friction coefficients evolution.

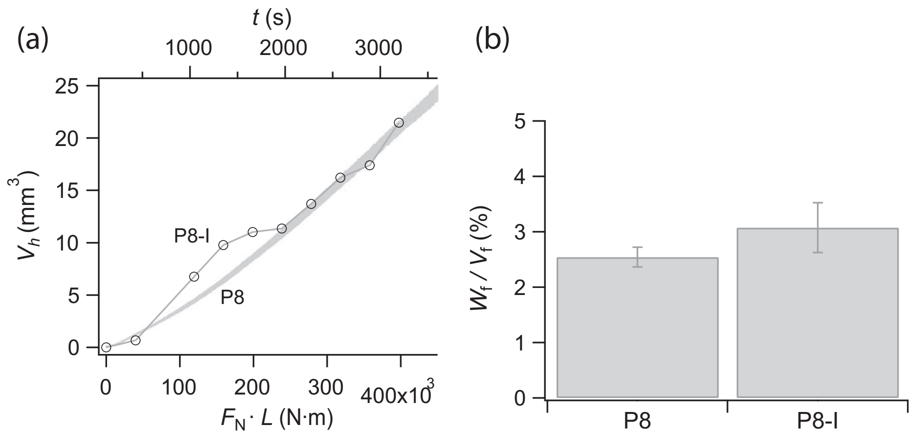

Fig. 9. Wear during experiments with the P18-I10 imbibed insert and of the P8 commercial insert: a — wear kinetics; b — ratio of the alumina final worn volume W_f and the inserts final worn volume V_f.

As a consequence of the improvements in the sintering process, the P8-I insert wear has not significantly increased in comparison to the insert P8. This wear similarity is confirmed by the same wear kinetic observed for these inserts (Fig. 9a). The P8-I insert has a mean wear rate of $5.9 \pm 0.5 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$ and the insert P8 a mean wear rate of $5.4 \pm 0.5 \cdot 10^{-5} mm^3 \cdot N^{-1} \cdot m^{-1}$. The final worn volumes ratio confirms that no significant change occurs during the studied conditions of sliding (Fig. 9b).

Reactive imbibition

The P8-RI insert reaches a friction coefficient of 0.80 ± 0.05 representing an increase of 14 % compared to the P8 insert (Fig. 10a). At the opposite, the P12-RI insert displays a friction coefficient of 0.44 ± 0.03 which is 31% lower than the base P12. The mean friction coefficient of the P16-RI insert (0.51 ± 0.16) is similar to the one registered by the P16 insert (median value of 0.61) but with a higher discrepancy.

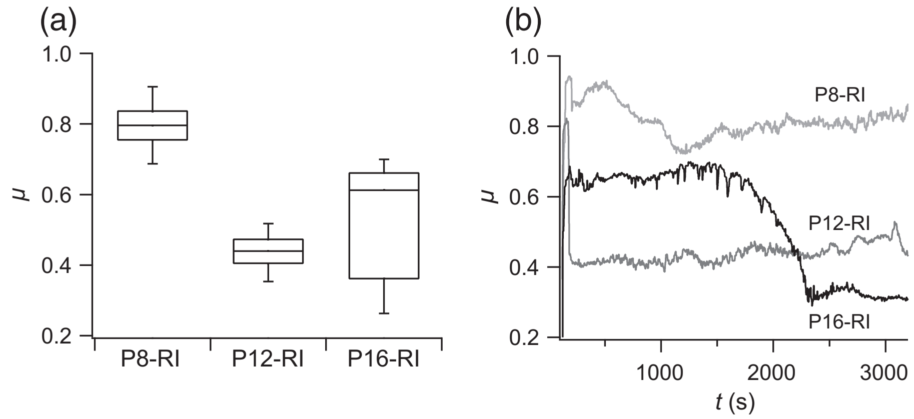

Fig. 10. Friction coefficients of inserts realized by reactive imbibition: a — box and whiskers chart with repeatability tests consideration; b — friction coefficients evolution.

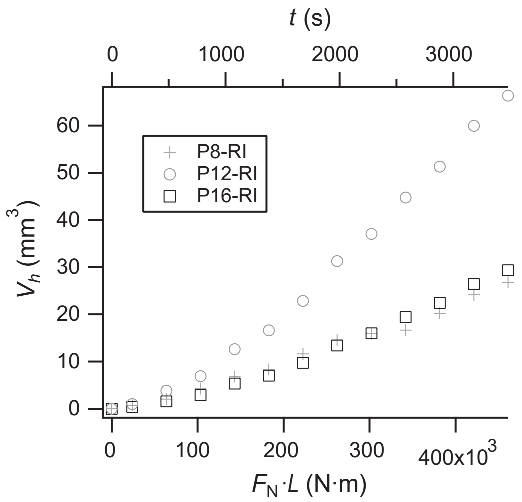

Fig. 11. Wear during experiments with the inserts realized by reactive imbibition.

Actually, the friction coefficient curve of the P16-RI insert is stable at 0.66 ± 0.03 until 1800 s (Fig. 10b), but drops to 0.32 ± 0.02 after 2300 s. These results indirectly indicate that the boride phases have an effect on the P8-RI insert friction all along the tests. Otherwise, the borides and the cobalt depletion on the insert P12-RI have a poor effect on friction. In addition, the P12-RI imbibition may be excessive with a too large cobalt migration from the bottom to the tip. Then the P16-RI insert mixed friction behaviour results from the boride phases effect during the first period and from the imbibed WC-Co volume rich in cobalt acting in the sliding contact during the second period.

The wear kinetics of the P8-RI and P16-RI inserts are quite similar and give the lowest mean wear rates (respectively $5.7 \pm 0.5 \cdot 10^{-5}\text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ and $6.5 \pm 0.5 \cdot 10^{-5}\text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$) (Fig. 11). The P8-RI wear rate is similar to the P8 one. The P16-RI insert has a wear rate 31% lower than the P16. The P12-RI insert has the highest wear rate ($14.4 \cdot 10^{-5}\text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$) representing almost three times the wear rate of the P12 insert. This result shows that the graduation treatment realized on this insert highly affects the wear resistance of the P12 commercial insert.

The counterface has in proportion an equivalent wear reaction towards the P8 or the P8-RI (Fig. 12). Once again, as for the P8-I insert, this result confirms that the graduation treatment has a little effect on the wear behaviour of the P8 based inserts. The results with the P12-RI lead to the opposite conclusion. This insert wears more than the base P12 and the counterface is also relatively less worn. The insert P16-RI not only has a better wear resistance than the insert P16, but also has also a better W_f on V_f ratio. In other words, the alumina counterface wears less in proportion than the insert P16 (i.e. $\frac{W_f}{V_f}<1$) and wear relatively more than the insert P16-IRP-10 (i.e. $\frac{W_f}{V_f}>1$).

Post-experimental characterizations

Inserts worn surfaces

As for the commercial inserts, abrasion scratches are visible on the graded insert worn surface. These scratches are clearly observable on the simply coated insert (i.e. P12-RC1 and P12-RC2) worn surfaces. The other graded inserts realized with an imbibition process display less defined scratches. These observations have to be related to the greater cobalt content of the imbibed inserts. During wear, the cobalt phase stabilizes the third body in the contact (see part 1) and explains higher material transfers on the imbibed insert worn surface. These transfers mask the abrasion scratches pattern.

Relatively to the P12 insert (Fig. 13a), the P12-RI insert worn surface displays a denser material transfer (Fig. 13b). Because of the high roughness of its worn surface, only the P12-RI insert has a visible and contrasted material transfer. The other inserts have observable abrasion scratches with a metallic shiny aspect on their worn surface.

Indeed, as previously found with commercial inserts, the amount of material transfer is also related to the formation of a high roughness on the worn surface. This high roughness is due to the extraction of coarse WC grains during wear and induces a high trapping of particles. The graded inserts maintain or reduce this roughness with respect to the base commercial inserts except for the P12-RI insert (Fig. 14).

SEM observations lead to a finer analysis of the material transfers. For example, the P12-RC1 insert has a similar worn surface than the commercial inserts: the light zones correspond to the WC-Co and the dark ones to the spreading of material transfers in the sliding direction (Fig. 15a). The P12-RC2 inserts has less dark areas corresponding to less transfers spread on its surface (Fig. 15b). Otherwise, the P16-RI insert shows a worn surface with a more homogeneous aspect (Fig. 15c). The dark areas are even more scattered than for the P12-RC2 insert and the light zones are also rarer than for the P12-RC1. At higher magnification (i.e. at the WC grains scale), the P12-RC2 microstructure is observable. For the other inserts this microstructure is hidden by greater material transfers. At this magnification, the dark transfer on the P12-RC1 is consistent with a ductile aspect. For the P12-RC2, the scattered transfers is formed by low conductor particles (i.e. alumina particles) forming charge phenomena during SEM observation of these areas.

Finally, the graded inserts also display transgranular cracking mechanisms affecting the WC grains (Fig. 15d). As for the commercial inserts, this mechanism forms smaller WC particles and grains are extracted and introduced in the third body.

Counterfaces worn surfaces

A general view of the alumina counterfaces provides additional information that overlaps with the analyses of insert worn surfaces. As for the counterface associated with the commercial inserts, the worn counterfaces from the tests with the simply coated inserts have shiny wear tracks (Fig. 16c and d). The counterface of the insert P16-RI (Fig. 16f) has partially a shiny track and a part of this track is also matt and grainy. For the counterfaces of the graded inserts P8-I and P8-RI (Fig. 16a and b), the wear track is totally matt and this aspect is accentuated for the counterface of the P12-RI (Fig. 16e).

In addition, these micrographs inform on the qualitative amount of debris ejected from the contact. The P12-RC2 and P8-RI counterfaces show a great amount of powder spread out of the wear track. This

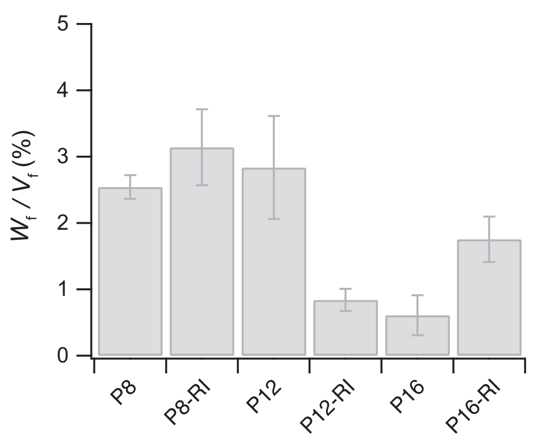

Fig. 12. Ratio of the alumina final worn volume W_f and the inserts final worn volume V_f.

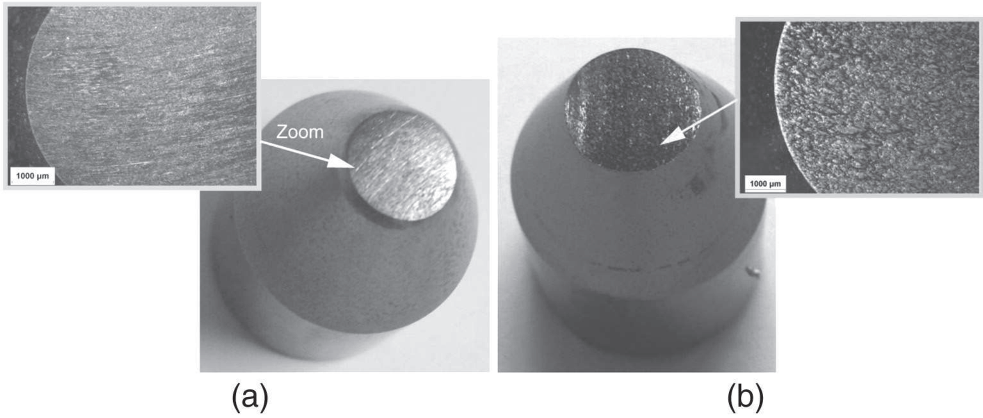

Fig. 13. General and microscopic views of worn surfaces and material transfers: a — insert P12; b — P12-RI.

phenomenon is more discrete for the P12-RC1 counterface. For the P16-RI counterface, a finer powder is spread homogeneously all over the non-worn surface. The other counterface associated with the inserts P8-I and P12-RI has little ejected particles.

Discussion

This study on the graded inserts completes the previous observations made with the commercial inserts in part 1. The description of the wear mechanisms through the tribological circuit remains suitable here.

The reactive coating realizes a hardening of the insert active surface by the formation of borides WCoB and the depletion of cobalt phase beneath this surface. Therefore, the internal flow Q_i is limited by the weak introduction of cobalt in the source flow Q_s and then a poor cohesion of the third body. Therefore, the friction coefficient increases as a consequence of a low accommodation by shearing in the third body. Also, the amount of cohesive abrasive paste in the contact is reduced which implies a better wear resistance for the coated inserts.

The imbibition can produce the opposite effect by enriching the insert core in cobalt. In the worst case, the imbibition can be counterproductive if the process is not correctly optimized as when a too important migration of cobalt reaches the active surface. In this case, the internal flow increases and an abrasive third body is more cohesive because of a source flow rich in cobalt. Hence, this third body has a dual effect: it leads to an increase of wear (abrasive effect) but also to a reduction of the friction coefficient (solid lubrication effect).

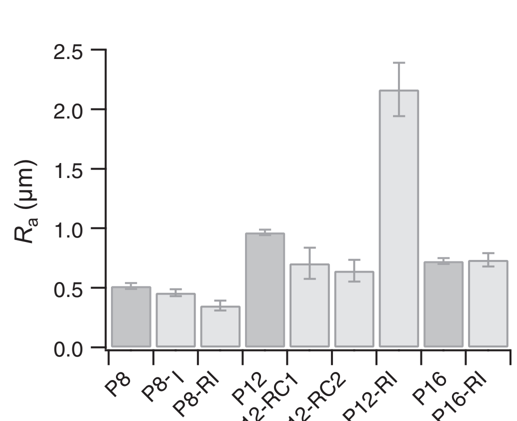

Fig. 14. Roughness of the commercial and graded inserts worn surfaces (profile arithmetic average R_a).

The WC grain size distribution is another parameter which is not concerned by the graduation processes. As previously explained, the WC grain size acts by dissipating energy in the contact and on the roughness of the worn surfaces. The worn surface relief regulates the internal flow.

Specifically, the P8 insert commercialized with the lowest cobalt content and the highest hardness has obviously the greatest wear resistance. Nevertheless, the realization of WCoB hardening phases can significantly improve the WC-Co insert properties and performances. Indeed, the reactive coating performed on the tough P12 insert improves its abrasion resistance (e.g. the P12-RC2 insert). The imbibition realized with a controlled and optimized cobalt migration can preserve the wear resistance of the base insert as for the P8-I insert with respect to the P8. Finally, the control of the reactive imbibition process can improve in the same time the fracture toughness of the insert core and the wear resistance of their active surface. A good example is the P16-RI insert with its high core cobalt content which presents an equivalent wear resistance to the P8 insert. At the opposite, a too important cobalt migration during the P12-RI manufacturing led to an excessive wear of this graded insert.

Conclusion

The tribological behaviour of graded inserts was studied and compared on the basis of the approach developed for the commercial insert in part 1. Three types of graded inserts were considered: the inserts with borides WCoB near their active surface, the inserts with cobalt enriched core by imbibition and the inserts with reactive imbibition combining the two previous processes. The WCoB phases increase the active surface hardness and the imbibed insert core increases the fracture toughness of the graded inserts. A third body approach shows that an optimized graduation process can reduce the cobalt source flow and the production of a cohesive and harmful abrasive paste in the contact.

On the innovative inserts, the wear tests showed that:

- The boride phases increase the wear resistance by hardening the active surface and limiting the cobalt content in the third body;
- The boride phases, as with the inserts cobalt content, lead to a reduction of the friction coefficient;
- The imbibition process realized with a controlled cobalt migration in the inserts preserves their high wear resistance. Again, the wear resistance can be maintained by avoiding a too high source flow of cobalt phase in the contact.

The commercial cemented carbides WC-Co can eventually be modulated to choose between a wear resistant and an impact resistant insert. The graduation processes are clearly a good way to create inserts with both qualities.

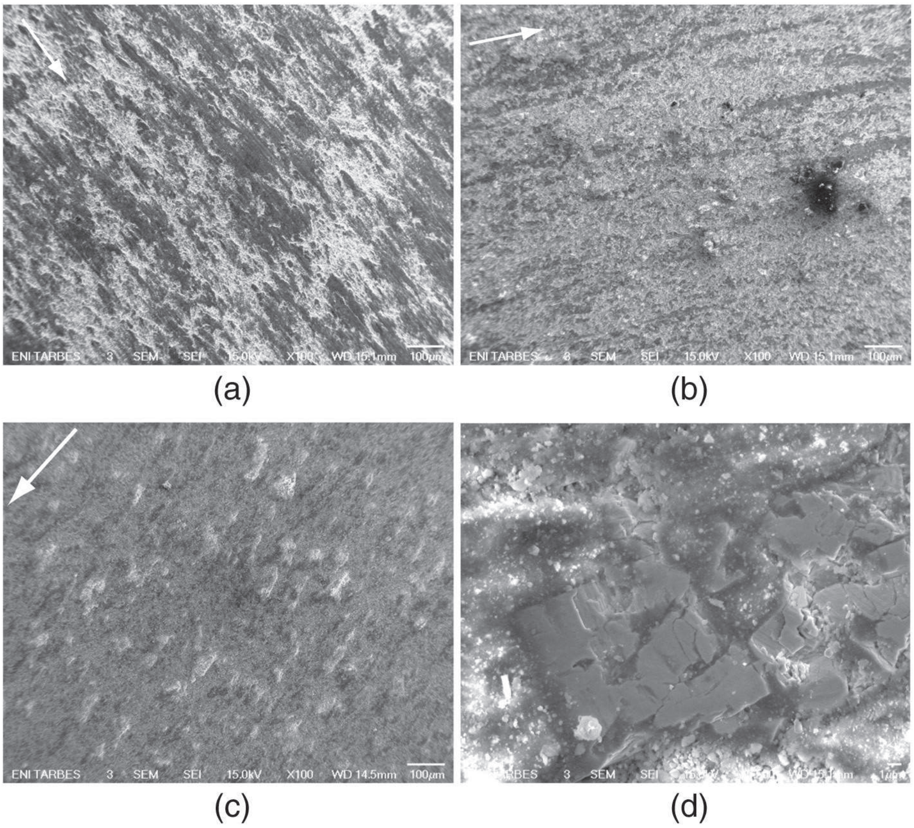

Fig. 15. SEM observations of graded inserts worn surfaces (the arrow indicates the sliding direction): a — P12-RC1; b — P12-RC2; c — P16-RI; d — P12-RC2 (WC grains scale magnification).

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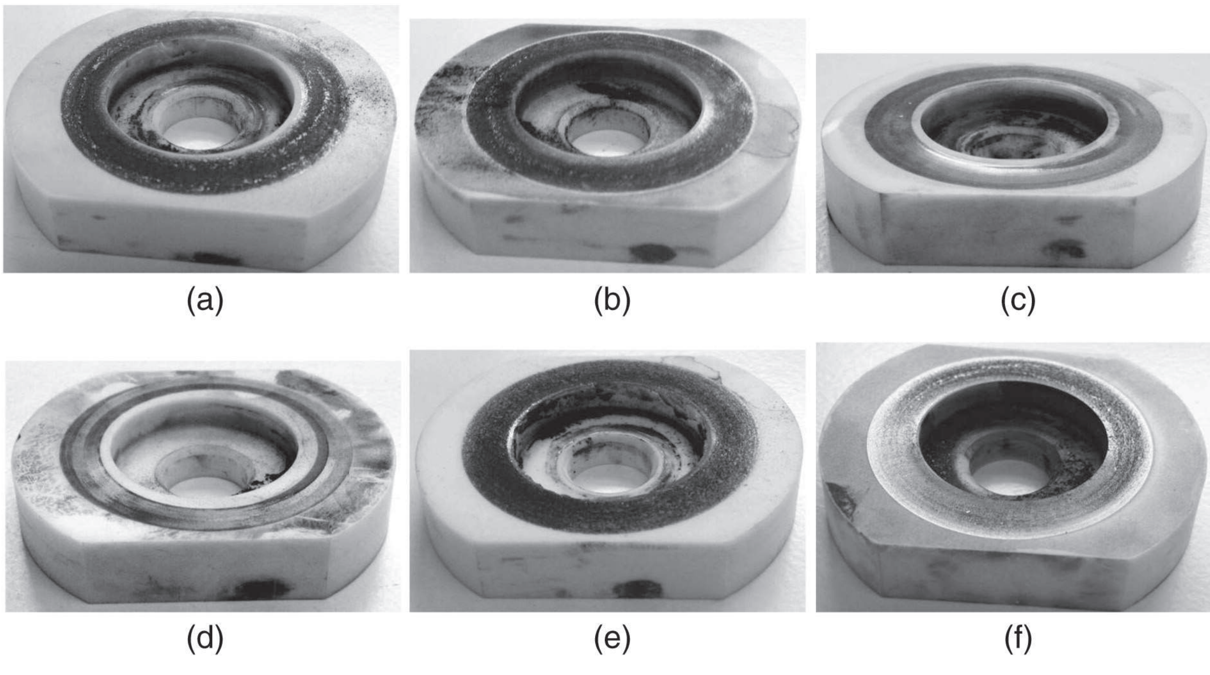

Fig. 16. Pictures of worn counterfaces associated with the graded inserts: a — P8-I; b — P8-RI; c — P12-RC1; d — P12-RC2; e — P12-RI; f — P16-RI.

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