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Abrasion of ultrafine WC-Co by fine abrasive particles

P. V. Krakhmalev

Department of Mechanical and Materials Engineering, Karlstad University, SE-651 88 Karlstad, Sweden

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Abstract: Abrasive wear of a series of WC-(5%−14%, mass fraction)Co hardmetals was investigated employing coarse and fine SiC abrasive under two-body dry abrasion conditions with pin-on-disc and edge-on-disc test arrangements. Unexpectedly, it is found that submicron grades demonstrate substantially higher wear rates comparing with the coarse grades if fine abrasive is utilized in pin-on-disc tests. Such a behavior is attributed to changes in a ratio of abrasive size to size of hard phase as finer abrasive is used. The edge-on-disc test demonstrates that edge wear may be described in two stages with the highest wear rates at the beginning stage. This behavior is associated with a transition of wear mechanisms as edge is wider due to wear. Compared with the ultrafine grades of the same Co content, the coarse grades demonstrate higher wear rates at the beginning, but lower wear rates at the final stage. Wear rates and mechanisms observed at final stage correlate well to the results observed for pin-on-disc tests employing fine abrasive.

Key words: WC-Co hardmetal; abrasion; edge wear; wear mechanisms; microstructural effect

1 Introduction

Abrasive wear of WC-Co hardmetals has been extensively examined last decades with a particular focus on the comparison of novel nanoscale and ultrafine composites to conventional WC-Co grades that usually demonstrate superior performance compared with the conventional WC-Co grades[1].

In common experience, the smaller the WC particles, the better the abrasion resistance of WC-Co hardmetals[1−2,4]. This trend has been observed using standard test methods utilizing high loads and coarse abradant of a few hundred micrometers in size[2−4]. Ploughing, fracture of WC grains and binder extrusion wear mechanisms[5−6] have been found usual wear mechanisms observed in abrasion of WC-Co hardmetals by the coarse SiC particles.

Nevertheless, as it has been illustrated in several recent researches[7−9], ultrafine grades may demonstrate higher wear rates in comparison with the conventional micron grades. This effect has been discussed in terms of the operative wear mechanisms, i.e. the rate of material removal by ploughing observed for the ultrafine grades may be higher than that for the preferable binder removal following by WC grains pullout, studied for the micron scale grades[9].

Although abrasive wear of WC-Co hardmetals has been investigated thoroughly using flat specimens, wear resistance of a sharp edge is still insufficiently understood. There has been a series of publications on flaking (or chipping) phenomenon in brittle materials including some hardmetals[10−12], and a correlation between the edge toughness and K_{IC} and G_{IC} values has been empirically confirmed[10,12]. Another attempt to evaluate edge wear mechanisms and to find a correlation between fracture toughness and abrasion resistance of WC-Co has been made in Refs.[13−14]. SCIESZKA [13−14] investigated edge wear phenomenon in a granular abrasive medium using prismatic specimens. It has been illustrated that the edge wear can be described in terms of unsteady and steady stage, and a transition between them has been related to a ratio between a plastic strain produced by abrasive particle and a critical plastic strain at which crack starts to propagate the material[13]. Such an approach is well correlated to edge wear mechanisms observed[15].

As it is seen from the foregoing discussion, there still are some challenges in understanding of abrasion micromechanisms of WC-Co. For instance in the real applications, size and nature of abrasive particles may vary significantly and be as fine as WC grains are, but

Corresponding author: P.V. Krakhmalev; Tel: +46-(0)54 700 20 36; E-mail: Pavel.Krakhmalev@kau.se

effect of a fine abrasive, especially acting at the edge, has not been properly investigated. In this study, influence of the fine abrasive and the microstructural parameters (WC grain size and Co content) on the wear mechanisms in series of WC-Co hardmetals was investigated under pin-on-disc and edge-on-disc dry two-body abrasion test arrangements utilizing SiC abrasive. The observed influence of the microstructure on wear resistance was discussed in a correlation to wear mechanisms examined with SEM.

2 Experimental

A series of WC-Co hardmetals of different Co content and WC grain size were investigated. Nominal chemical composition and selected mechanical properties of the tested grades are listed in Table 1. The specimens were ground and polished, edge specimens were polished at two sides forming the 90˚ edge with 3 μm diamond finishing paste. An example of the polished edge of the C9 specimen is given in Fig.1(a).

A sketch of the specimen arrangement and sliding geometry for edge-on-disc tests is shown in Fig.1(b). Pin-on-disc tests had the same geometry, and the diameter of the pin was 3.2 mm. To achieve the required sliding distance, specimens slid along the fresh abrasive surface until the required distance was accomplished as a number of ring tracks.

Worn specimens were examined with a GEMINI LEO 1530 scanning electron microscope(SEM) to observe the surface morphology and measure the widths of the worn edges. Wear rate (volume loss per unit sliding distance) values are equal to the coefficient A in the linear equation $Y=AX$ (where Y is the volume loss, X is the sliding distance, A is the coefficient) interpolating experimentally obtained data. In a case of edge specimens, four initial and four final points were used for the interpolation of beginning and final stages respectively and, calculated coefficient of determination R^2 varied in a range of 0.96−0.99 for all the trend lines. The width of the worn surface vs sliding distance diagram

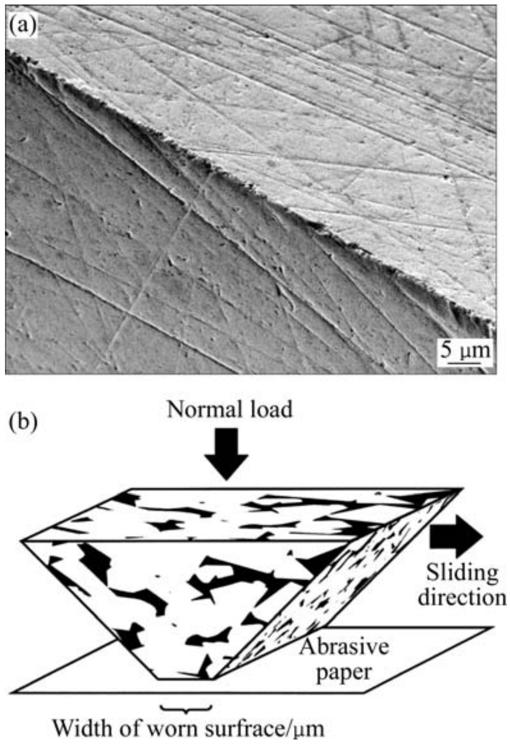

Fig.1 Edge of polished C9 specimen (a) and sketch of specimen arrangement and sliding geometry (b)[16]

was preferred to the commonly used worn volume vs sliding distance dependence due to better graphical visualization of the experimental results (parabolic shape of the diagram, differentiation of the beginning and final stages and cross-points are better distinguishable).

3 Results and discussion

3.1 Pin-on-disc tests

In all the observed cases, a typical Archard's linear dependence of the volumetric wear on sliding distance was observed. Wear rates calculated from the slope of trend lines fitting each experimental data series are shown in Fig.2. It can be seen that if the fine P800 abrasive is utilized, ultrafine and nanoscale WC-Co grades demonstrate higher wear rates compared with the

Table 1 Designations, nominal chemical composition and mechanical properties of investigated WC-Co grades

Designation	Grain size/μm	w(Co)/%	Hardness, HV30	Fracture toughness/(MPa·m$^{1/2}$)	Transverse rupture strength/(N·mm^{-2})
UF5	0.3	5	2 150	5.6	3 900
UF6	0.3−0.5	6	2 050	6.2	3 900
EF6	0.5−0.9	6	1 850	8.8	4 400
MC6	2.5	6	1 450	13.0	3 710
C6	4.5	6	1 290	17.0	3 300
N7	0.2−0.4	7	1 900	9.0	5 100
N9	0.1−0.3	9	1 950	8.0	4 700
C9	4.5	9	1 210	20.0	3 400
C14	1.5	14	1 050	24.0	3 180

coarse grades. For example, wear rate for the C6 grade was about 3 times lower than that for the UF6 grade containing the same Co content. In all cases, increase of Co content led to increase in wear rates.

Worn surfaces after abrasion by coarse and fine SiC particles are shown in Fig.3. Extensive plastic deformation, fracture, defragmentation and pullout of WC grains were observed on worn surfaces of coarse WC-Co grades abraded by the coarse abrasive. For ultrafine and nanoscale grades abraded by the coarse SiC, ploughing with some indication of microfatigue was examined. After abrasion by fine abrasive particles, worn surface morphology is remarkably different. Preferential binder removal with some damage of WC grains was observed for the coarse grades abraded by fine abradant. For ultrafine and nano WC-Co grades abraded by the fine SiC, formation of grooves on the worn surface was observed.

The total wear depends on test conditions and size of abrasive particles is one of the most important parameters of a tribosystem. Recently, it has been demonstrated that a ratio of abrasive size to size of hard phase may be more efficient parameter for analysis of the abrasive wear behavior than size of abrasive particles

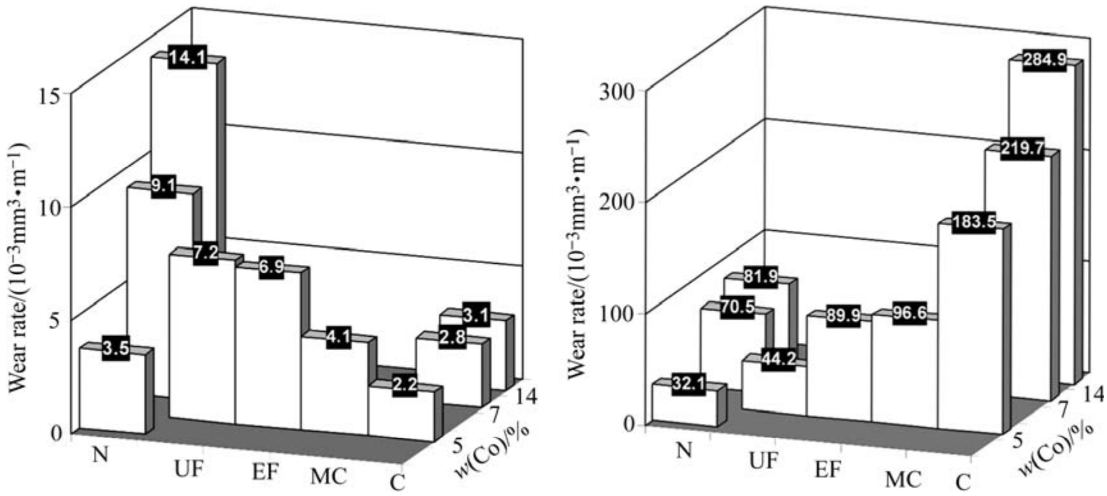

Fig.2 Wear rates for abrasion of WC-(5%−14%, mass fraction) Co hardmetals by P800 SiC (a) and P120 SiC (b) abrasive papers: N 0.1−0.3 μm; UF 0.3−0.5 μm; EF 0.5−0.9 μm; MC Mean 2.5 μm; C Mean 4.5 μm

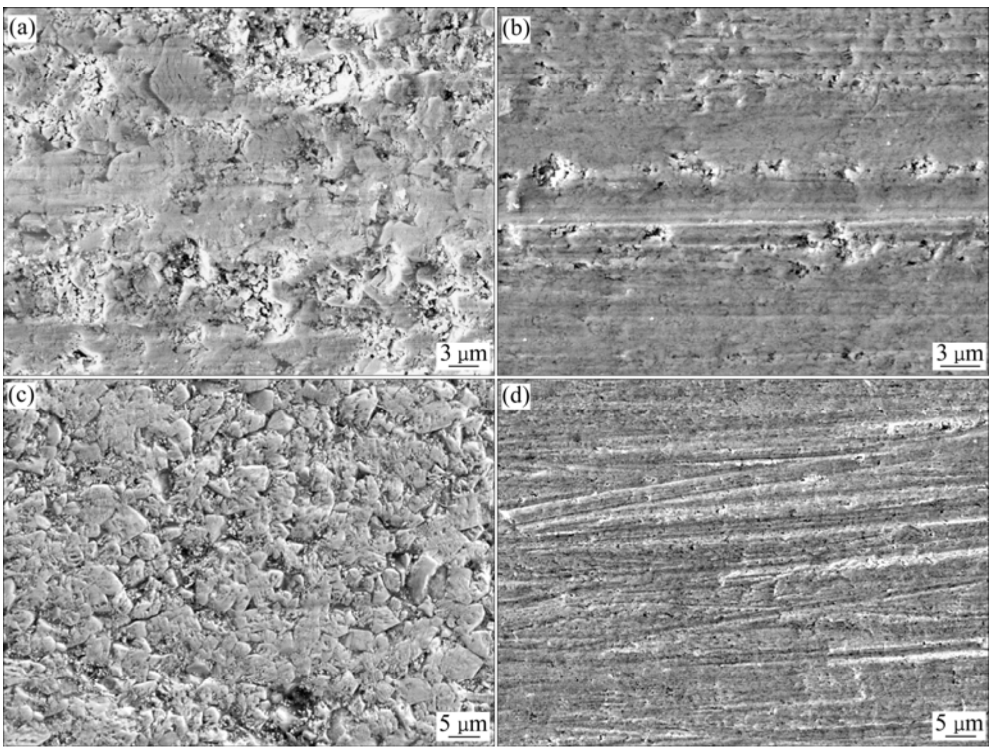

Fig.3 Surface morphologies of WC-Co hardmetals (sliding direction is from left to right in all images): (a, b) Abraded by coarse abrasive; (c, d) Abraded by fine abrasive

[16]. The computational analysis has shown that the wear loss increases with increasing size ratio and becomes stable when the ratio reaches a certain level, close to the unity. This behavior has been explained in terms of different wearing stress distribution in case of fine and coarse abrasive particles[16].

The conclusions above are in a good agreement with the results obtained in the present research. As seen in Fig.3, for coarse WC-Co grades, acting wear mechanisms are different if coarse or fine abrasive particles are utilized.

In a case of the coarse abrasive, size ratio is higher than the unity. Therefore, microstructure of WC-Co composite responds homogeneously providing simultaneous deformation or fracture of both phases so that fragmentation, pullout and plastic deformation were the main detected wear mechanisms. Decrease of the abradant size led to changes of size ratio closer to the unity. This resulted in heterogeneous response of the WC-Co composite. Consequently, preferential binder removal was the dominating wear mechanism.

In the case of ultrafine and nanoscale WC-Co grades, changes in the abrasive size did not result in changing of wear mechanisms because the size ratio value did not reach the critical level. Hence, ultrafine WC-Co hardmetals showed homogeneous response. These findings confirm suggestion that when abrasive is smaller than the certain critical value, loss of matrix is the main wear mechanism; when abrasive size exceeds the critical value, wear loss could be related to fragmentation and pullout of the reinforcing phase.

The foregoing changes in wear mechanisms dramatically influenced wear rates and, surprisingly high wear rates (Fig.2(a)), were detected for ultrafine and nanoscale WC-Co grades, as the fine SiC abrasive was utilized. This is well correlated to the assumption that preferential binder removal observed for abrasion of coarse WC-Co grades by the fine SiC abrasive provides lower total wear comparable to the wear by plastic deformation and fracture. In a case of the coarse SiC abrasive, wear is governed by ploughing and materials demonstrate ordinary behavior, i.e. coarse materials have about 4 times higher wear rates compared with the ultrafine and nanoscale WC-Co grades.

3.2 Edge-on-disc tests

The wear diagram for investigated WC-Co grades is shown in Fig.4. As is seen, the dependence of the worn width on sliding distance has a parabolic character with the highest wear rates are at the beginning stage of sliding, while after longer sliding wear rates gradually decrease.

Comparison of the experimental results for materials of the same WC grain size but different Co contents demonstrates gradual rise of the worn width as the Co content increases (full lines for the coarse C6, C9 and C14 grades and dashed lines for the ultrafine UF5, UF6 and UF9 grades in Fig.4).

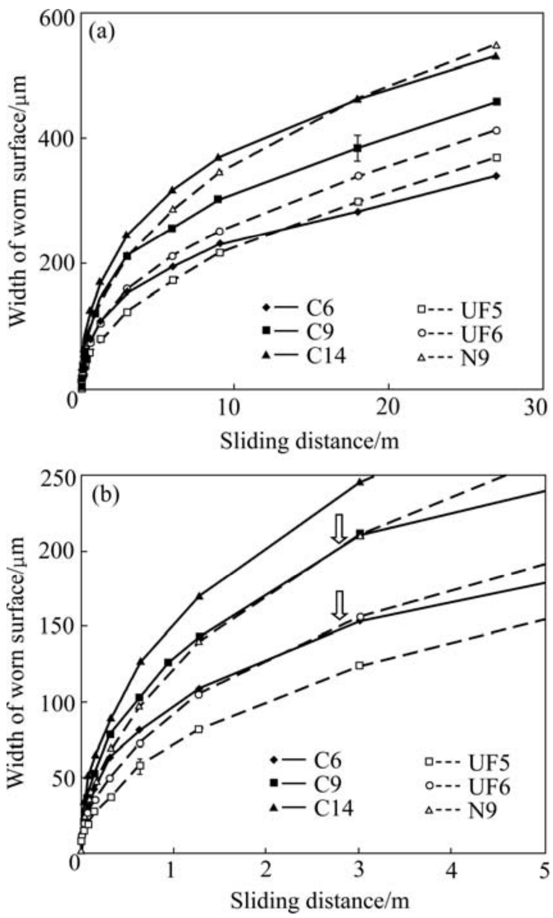

Fig.4 Width of worn surface vs sliding distance diagram (a) and close view of beginning part of diagram (b) (Cross-points observed for lines corresponding to 6%Co C6 and UF6 grades, and 9%Co C9 and UF9 grades are marked by arrows [17])

Comparing the C6 with UF6 and the C9 with N9 pairs of the tested grades (Fig.4), it is seen that the lines are crossed after about 3 m sliding distance. Thus, the coarse C6 grade showed higher wear at the beginning stage, but after certain sliding distance, higher wear corresponded to the ultrafine UF6 grade. Exactly the same situation observed for the C9 and N9 grades (Fig.4(b)). After 27 m sliding, the ultrafine grades showed higher worn widths than the coarse grades, comparing the grades of the same Co content (C6 with UF6 and, C9 with N9). The highest worn width after 27 m sliding was detected for the N9, and the lowest for the C6 grades.

Fig.5 shows the worn surfaces observed after selected sliding distances in the tested grades. It is seen from Figs.5(a)−(c), that fracture, plastic deformation and pullout of the WC grains are the main edge wear mechanisms in the coarse grades at the beginning stage.

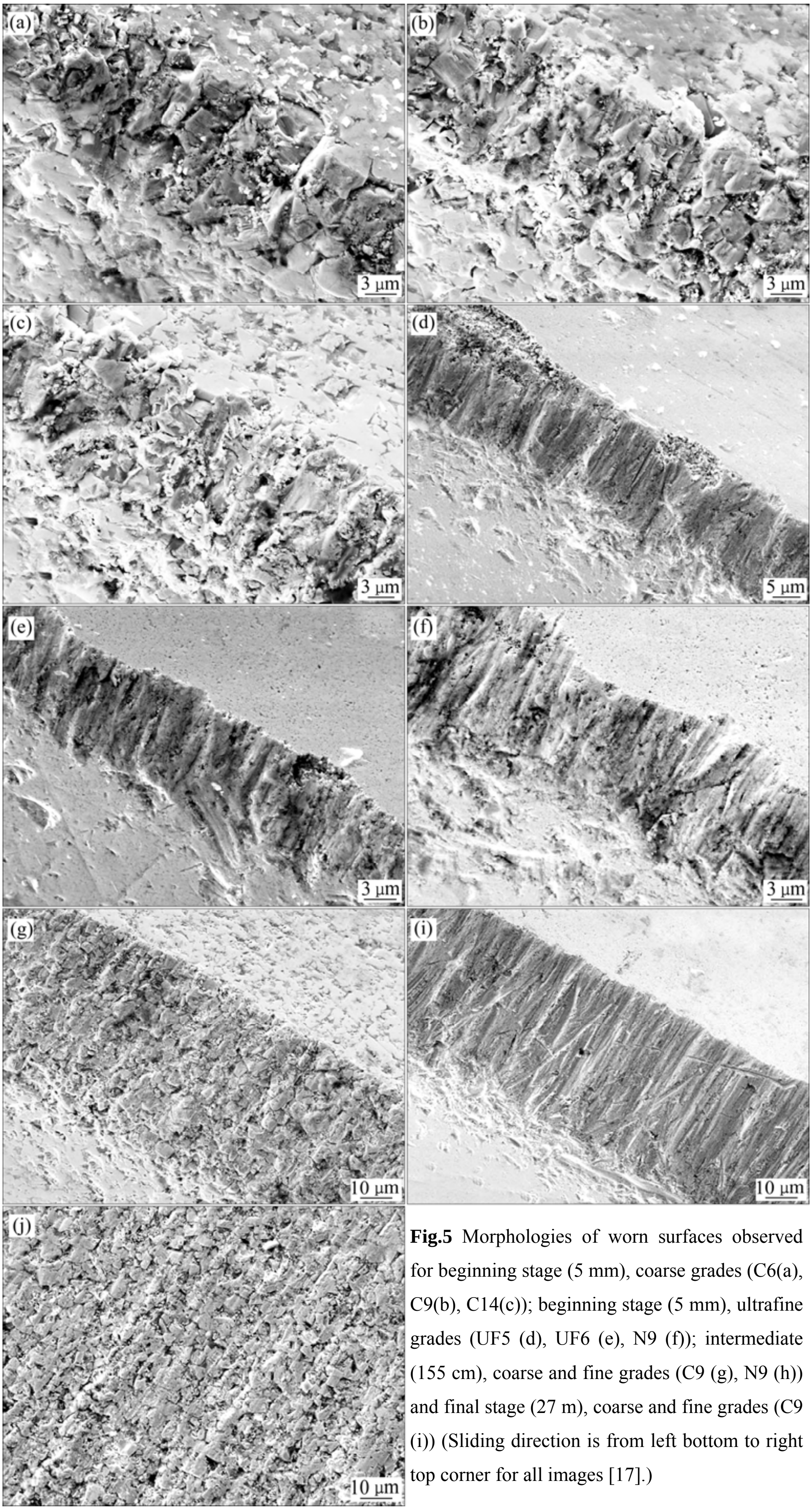

Fig.5 Morphologies of worn surfaces observed for beginning stage (5 mm), coarse grades (C6(a), C9(b), C14(c)); beginning stage (5 mm), ultrafine grades (UF5 (d), UF6 (e), N9 (f)); intermediate (155 cm), coarse and fine grades (C9 (g), N9 (h)) and final stage (27 m), coarse and fine grades (C9 (i)) (Sliding direction is from left bottom to right top corner for all images [17].)

For the ultrafine grades, ploughing is the main wear mechanisms observed for all the grades, Figs.5(d)−(f), but some chipping was detected for the UF5 and UF6 grades (Figs.5(d) and (e)).

Further sliding led to change in wear mechanisms. At the final stage, after 27 m sliding distance, morphology of worn surface was found similar to the one observed for pin-on-disc specimens, i.e. preferable binder removal following by pullout of the WC grains is the main acting wear mechanism (Figs5(g)−(i)). Ploughing is the main wear mechanism for the ultrafine grades (Fig.5(h)). Comparing values of the worn widths at different stages it is seen that the worn width for the ultrafine grades exceeds the width for the coarse grade for about 15%−20% at final stage.

Recent analysis of the edge behavior[13−14] demonstrated that observed wear rates may be described with a parabolic-type dependence. In this approach[11], the edge wear is described in terms of unsteady (beginning) and steady (final) stages, which depends on correlation between a plastic strain, ε_p, produced by the asperity and a critical strain, ε_c, at which a crack starts to propagate into the bulk. Following this concept, the beginning or unsteady stage corresponds to the case of $\varepsilon_p > \varepsilon_c$, while steady stage to the $\varepsilon_p < \varepsilon_c$ case[13]. If $\varepsilon_p < \varepsilon_c$, the wear rate is described by the Archard's equation and depends mostly on hardness of the specimen. Otherwise, when $\varepsilon_p > \varepsilon_c$, the wear rate depends on both hardness and fracture toughness of the material.

Applying this approach to the edge wear of coarse WC-Co grades, it is possible to conclude that the strain produced by asperity will exceed the critical for the failure strain value rather at the beginning stage. Then, the specimen is sharp and, if fine abradant is used, only few WC grains are in a contact area. Therefore, pullout or fracturing and detachment of WC grains, caused by strain localization in the binder or carbide phase, are the most possible wear mechanisms at this stage. Further sliding leads to increase in the contact area, redistribution of strains and, therefore, changing of the operative wear mechanism. In case of ultrafine grades, contact area exceeds features of the microstructure and therefore, strains more homogeneously distributed into the bulk. Thus, a homogeneous behavior causing, for instance ploughing is most likely expected in ultrafine grades under the described conditions.

Influence of the WC grain size on wear mechanisms observed experimentally is shown in Fig.5. At the beginning stage for the coarse grades, fracture and pullout of the WC grains (Figs.5(a)−(c)) are the main wear mechanism. After longer sliding distances, a transition in wear mechanisms take place and, preferable binder removal followed by WC grains detachment was observed. For the ultrafine grades, ploughing wear was discovered over all the sliding distances. As is seen, the experimental results correspond well to the predicted differences in wear mechanisms for coarse and fine WC-Co materials abraded by fine abrasive.

In order to illustrate influence of transition in wear mechanisms on the wear rates, apparent wear rates were calculated for the beginning and final stages for each grades (Fig.6). At the beginning stage, higher wear rates correspond to the coarse grades. In other words, fracture, fragmentation and pullout of WC grains detected at the beginning stage for the coarse grades caused more severe wear than ploughing observed for the ultrafine grades. Comparing wear rates for C6, UF6 and, C9, N9 pairs at the beginning stages, it is seen that sliding distance to the same width of worn surface for ultrafine grades is 25%−40% longer than that for coarse grades.

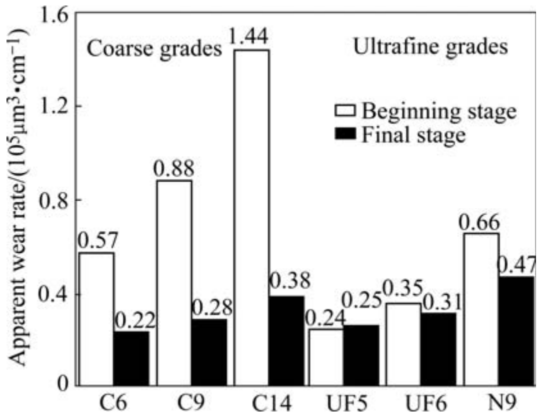

Fig.6 Apparent wear rates calculated at beginning (white blocks) and final (black blocks) stages for investigated WC-Co grades [17]

After certain sliding distance wear causes increase in contact surface and therefore, effect of the edge descends. This leads to the transition in wear mechanisms and affects wear rates dramatically. This transition of edge to flat-type behavior takes place in a region of 1−9 m sliding distance where both mechanisms act simultaneously and, therefore, is difficult to be precisely defined. The wear rates calculated at the final stage for the coarse and ultrafine grades are not so different, but higher for the ultrafine grades and also increases with increase in Co content. It is well consistent with the wear rates observed for the flat specimens worn by fine abrasive.

4 Conclusions

1) If fine abrasive is utilized under pin-on-disc conditions, surprisingly, submicron grades demonstrate substantially higher wear rates compared with the coarse grades. If the coarse abradant is used, better wear resistance of ultrafine and nanoscale WC-Co grades is

observed. It is shown that observed transition in wear mechanisms may be attributed to changes of the size ratio (a ratio of abrasive size to size of hard phase) as different abrasive was used.

2) Experimental results of edge-on-disc tests demonstrate that compared with the ultrafine grades of the same Co content, the coarse grades have 25%−40% higher wear rates at the beginning stage, while after longer sliding the wear rates for the coarse are higher than those for ultrafine grades. This behavior is associated with a transition in wear mechanisms operating at the beginning and final stages. Morphology of worn surface and wear rates observed at final stage of edge-on-disc tests are found similar to the pin-on-disc test results that indicate the edge effect on wear mechanisms is vanished.

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