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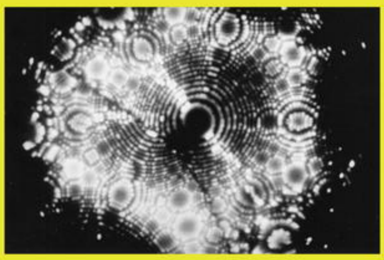

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Hot-press sintering temperature response of diamond cutting tools and its correlation with wear mechanism

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ABSTRACT

The diamond cutting tools (DCTs) find vast applications in the stone cutting industries. The properties of marbles/stones vary from mine to mine. The main factor judging the performance of the tool is its wear resistance which is primarily affected by materials/process variables and unpredictable working conditions. The DCTs having composition (by wt.%) of 13.5% Cu, 20% Co, 10% FTC, 6% Al, and 1% Mg and balance thermally reduced electrolytic iron powder were blended in a mixer with ball to powder ratio of 10:1 (by wt.%) for 2 h. Then this blended powder is mixed manually with synthetic diamonds (2.88%) and 2% paraffin wax. The blended powder was green compacted to size 20 mm × 10 mm × 4.5 mm in hot-pressed sintering furnace. The sintering response of DCT was studied and it was correlated with its wear performance in dry sliding Pin-On-Disc wear test machine having sintered alumina as the counterface. These specimens were subjected to varying loads (2, 6, 10, and 12 kg) and varying velocities (1, 2, 3, and 4 m/s) for wear test. The 2D contour was drawn to establish transition in wear modes from adhesive wear to abrasive wear.

1. Introduction

Primarily diamond cutting tools (DCTs) are traditionally manufactured using carbonyl iron as one of the main constituents of the matrix. However, in light of the cost, the manufacturers are increasingly trying for thermally reduced electrolytic iron powder without compromising on the quality of the product. Number of operating conditions such as feed rate, depth of cut, peripheral speed, load, pressure, velocity, cutting mode, properties of rock, working conditions etc. governs the wear rate of DCT [1,2]. Ideally the wear rate of matrix and the diamonds should be equivalent but the excess wear of the matrix leads to pullout and wear of the diamonds. This lowers the efficiency of the tool [3]. The diamonds may also get graphitized/oxidized at higher temperature and thus diamond cutting tools are generally manufactured at sintering temperature below 1000 °C [4–6]. The specific wear rate (SWR) and specific energy (SE) change according to the cutting parameters. SWR is the most widely used parameter to measure the efficiency of a cutting process [7]. The sliding wear is mainly classified into three types viz. ultra mild (occurring at very low load), mild and severe wear. The wear rates increase with increasing load and sliding velocities. The severe wear rate usually possesses three orders higher magnitude than mild wear [8]. The friction and wear mechanisms of WC–Co carbide tools have been studied at varying speeds with constant load conditions. The temperature rise at the high speed leads to transfer of thermal energy from disc to pin causing removal of tool material [9]. The wear map was plotted based on different sliding conditions to predict the mild oxidational wear [10]. There is a need to investigate the stability of DCTs at various levels of loads and sliding speeds. These maps are becoming meaningful criterion for parameter selection and for failure analysis involving wear situations. It provides basis for selecting optimum operating variables and can be useful in locating working domain for practical application.

There are inadequate literatures on wear mechanism of diamond cutting tools especially application of electrolytic iron powder as the principal matrix. In the proposed work, the attempt is made to correlate the dry sliding wear of DCTs with the elevated temperature stability of diamonds at varied sintering temperatures. The proposed work helps to improve our understanding on wear mechanism of diamond cutting tools.

2. Experimental work and procedure

2.1. Fabrication of DCT

The major principal powder was thermally reduced (TR) electrolytic iron powder supplied by Industrial Metal Powder Pune. Initial blending was carried out by mixing powders except diamonds as indicated in Table 1 and was blended in laboratory mixer with a ball to powder ratio 10:1 (by wt) for fixed duration of 2 h. The blended powders were then mixed with calculated quantity of diamonds and 2% paraffin wax to homogenize the mixture. The blended powder was then compacted at a compacting pressure of 34 MPa in hydraulic compacting machine (M/s Supercut, Mumbai) to make DCT of size (20 mm × 10 mm × 4.5 mm). Afterwards these green compacts were placed in between graphite plates

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Table 1
Properties of the powders used for manufacturing of diamond cutting tools.

Sr. no.	Powder	Particle size (μm)	ASTM particle size (mesh)	Apparent density (g/cm^3)
1	Electrolytic iron (TR grade)	2.4	2400	1.3
2	Electrolytic copper	4.5	2400	1.2
3	Cobalt	1.45	4800	1.4
4	Nickel	105	140	4.1
5	Fused tungsten carbides (FTC)	37–44	75	6.07
6	Aluminum	91	140	1.18
7	Magnesium	52	270	0.64
8	Synthetic diamonds	250–300	50/60	3.52

of the die and then heated (80 °C/min) to 850 °C, 900 °C and 950 °C in hot pressed sintering furnace for 3 min using resistance heating furnace powered by 2-phase transformer (440 V, 20A) with a total duration of 17 min. Simultaneous stepped pressure starting from 10 MPa to 34 MPa was applied during sintering. DCTs were then furnace cooled upto 475 °C and then air cooled. The composition of DCT (by wt.%) was 46.6% Fe, 13.5% Cu, 20% Co, 10% FTC, 6% Al, 1% Mg and 2.88% synthetic diamonds. In this electrolytic iron was primarily used for fabrication of diamond cutting tools.

2.2. Characterization of DCTs

The fabricated DCTs were characterized for hardness, density and wear rates. The hardness was measured on Rockwell B-scale (HRB). The density was calculated by Archimedes' principle. The dry sliding wear tests of DCTs were undertaken on Pin-on-Disc wear test machine (M/s Magnum Engineers, Bangalore) integrated with MAGVIEW-2009 software for acquisition of wear data. Sliding pin of DCT having a cross sectional area of 45 mm^2 was fixed perpendicular to the rotating circular disc of sintered alumina disc (diameter 165 mm) having Mohr's hardness 7 as the counter surface. The surface roughness of the disc was maintained by polishing with 150 grit paper and the disc was cleaned with acetone from time to time to remove surface contaminations. New track radius of disc and new specimen were used for every change in the test parameter. DCTs were subjected to varying loads (2, 6, 10, and 12 kg) and varying velocities (1, 2, 3, and 4 m/s) for a sliding distance of 3000 m. A set of 16 points (matrix of 4×4) was obtained from each of the four values of load and velocity. All the wear rate values were reported based on the average of three readings of three samples. 3D surface response and 2D contour were drawn using the software. The worn surfaces were analyzed using scanning electron microscope (JOEL, JSM6360 A).

3. Results and discussion

During wear test, sliding pin of DCT encounters a rise in sliding surface temperature which leads to the oxidation and softening of the matrix. Such interfacial rise in temperature is responsible for altering wear mechanism by way of loosening and fracturing of diamonds either. Thus increase in sliding surface temperature can be correlated with sintering temperature of DCT. It may be noted that diamonds in the matrix experience temperature fluctuation both in sintering and wear test. In nut shell, diamond in the matrix is sensitive to temperature.

3.1. Influence of sintering temperature on DCT properties

The sintering temperature was varied in steps to correlate the effect on properties of DCT. The maximum hardness is observed at 900 °C as depicted in Fig. 1a. The increase hardness at 900 °C can be attributed to stability of diamond as well as to solid solution strengthening of the alloying elements of the matrix. Beyond 900 °C, the diamond loses its hardness property by way of graphitization and hence there is a drop in hardness. However, sintered density continued to rise with increasing sintering temperature as depicted in Fig. 1b. This trend can be correlated to liquid phase formation by low melting elements like aluminum (660 °C) and magnesium (650 °C) and thus results in reduction in porosity in the matrix. The improved wear resistance of DCTs is also corroborated by the retention of sharp cutting edges of diamond particles (Fig. 2a, b) till 900 °C. But further increase in sintering temperature to 950 °C (Fig. 2c) weakens the diamond particles which results in fracturing of diamonds during sliding as a result of tangential forces. It may be noted that synthetic diamond starts graphitizing beyond 900 °C [12]. The wear rate almost attained a steady state for the sintering temperature in the range of 850–900 °C and a slight increase in trend in wear rate is seen at 950 °C (Fig. 1c).

3.2. Wear mechanism

Based on the sinterability of DCTs at various temperatures, an optimum sintering temperature of 850 °C was chosen to fabricate DCTs and was tested for hardness and plotted wear curves. An average hardness was 106 HRB with a deviation of ±3HRB. Similarly the average sintered density was found to be 7.03 g/cm^{3}with a deviation of ±0.03 g/cm^3. Two extreme loads (2 and 14 kg) for varying levels of sliding speed and two extreme velocities (1 and 4 m/s) with varying levels of loads were plotted in Figs. 3 and 4 to identify wear regimes. The purpose of selecting these extreme conditions was to resolve

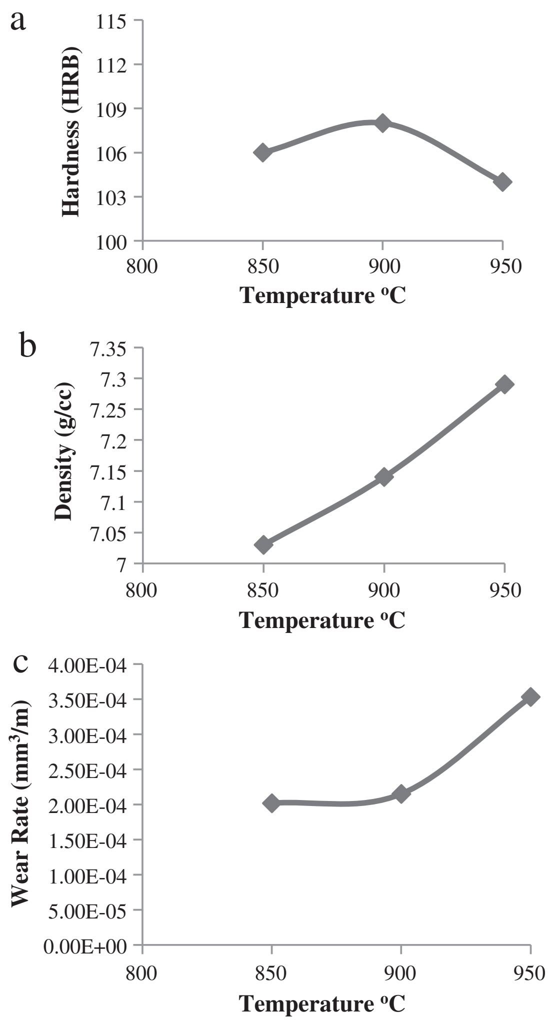

Fig. 1. (a, b, and c): Effect of sintering temperature on the properties of diamond cutting tools.

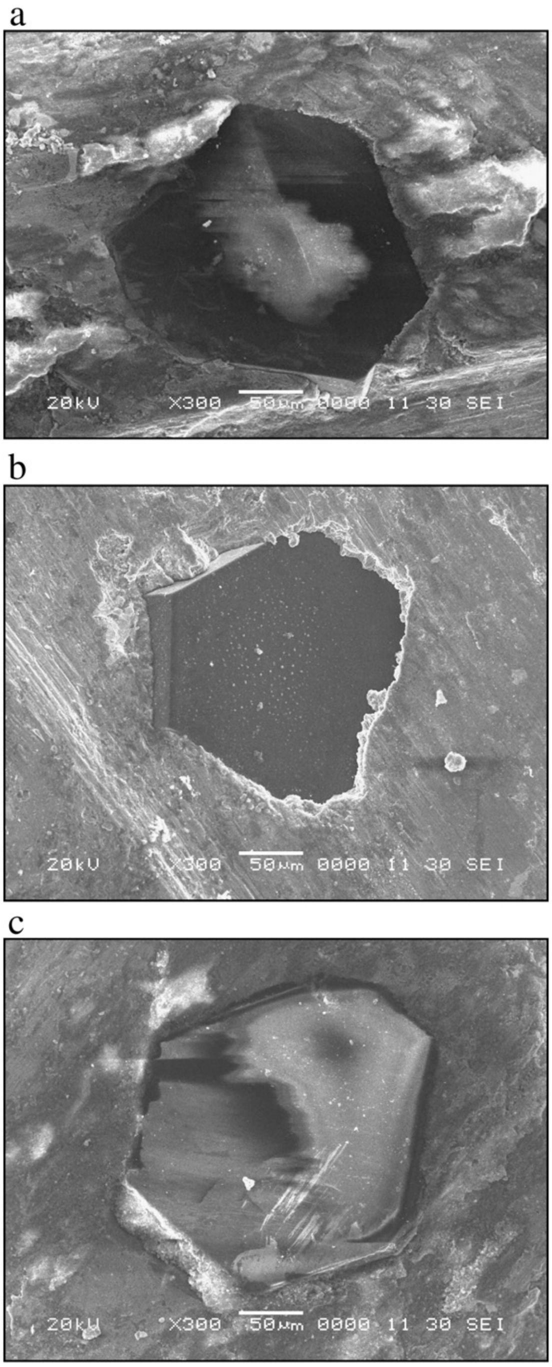

Fig. 2. (a, b, and c): SEM photograph of diamond cutting tools depicts retention ability of diamonds at higher sintering temperatures.

the wear regimes such as mild wear and severe wear regime. A combined effect of sliding speed and applied load was plotted against wear rate to generate 3D surface response for overall interpretation.

3.2.1. Effect of load on wear rates

The effect of varying loads on wear rate at constant velocity is shown in Fig. 3. The wear rate increases with rising load for both the chosen velocities. The plastic deformation induced by dry sliding can lead to loss of material by way of simultaneous wear of matrix and diamonds. DCT exhibits low wear rate at lower load and lower velocity. Overall, there is a slight increase in wear till 6 kg load then almost decrease for the range of 6 to 10 kg followed by a steep rise in wear rate. The highs in wear curves are attributed to exposure to fresh sliding surface for wear to occur and the lows correspond to the formation of oxide debris

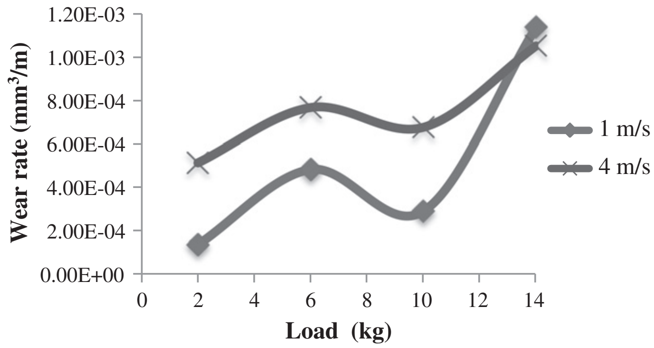

Fig. 3. Effect of varying loads on the wear rate of DCTs.

which stuck to the sliding surface and thus protects the wearing surface. Beyond 10 kg, severe wear is dominant which is attributed either to loosening of diamond particles from the matrix and the loss of cutting ability of diamonds due to graphitization [11] with simultaneous lose of matrix due to abrasive action of wear debris. Thus the fact can be correlated with the sintering response of DCTS as described in Fig. 2.

3.2.2. Effect of velocity on wear rate

The effect of varying velocities on wear rate was studied keeping load constant is shown in Fig. 4.The wear increases and thereafter decreases with increasing velocity. It is obvious that increasing sliding speed increases the sliding surface temperature which in turn oxidizes the surface. The oxidized debris stuck to the sliding surface and thus protects the further loss of wearing surface. While in case of 2 kg load, the wear rate increases till 2 m/s and thereafter it falls slightly and then almost remains steady with increasing velocity. The fall in wear rate for higher loads with increasing sliding speed could be attributed to formation of mechanical mixed layer at the sliding surface due to accumulation of oxide debris which protects the further loss of material.

3.2.3. Wear mapping of diamond cutting tool

The combined effect of load and sliding speed is realized by plotting 3D surface response and the 2D contour is shown in Fig. 5. The improved performance is shown by DCTs upto 6 kg load for all the velocities attempted as evident from 2D contour. It is dominated by adhesive wear mode (Fig. 6a). Beyond 6 kg, severe wear of DCTs is noticed which is dominated by abrasive wear mode (Fig. 6b). It is interesting to note that the worn surfaces of adhesive wear mode show only the smooth deformed surfaces and no grooving marks. It indicates that the diamonds may not dislodge from the matrix and retain its cutting ability (Fig. 2). Whereas, abrasive wear mode clearly shows the severe discontinuous grooving marks which might come due to fracturing of diamonds as the temperature of the sliding surface goes beyond 900 °C [Fig. 1c]. Besides, higher load results in high temperature rise at the sliding surface thereby softening the matrix. This gives rise to loss of mechanical properties of the matrix

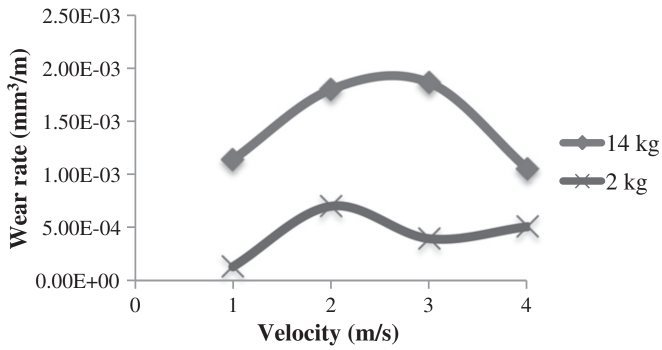

Fig. 4. Effect of varying velocities on the wear rate of DCTs.

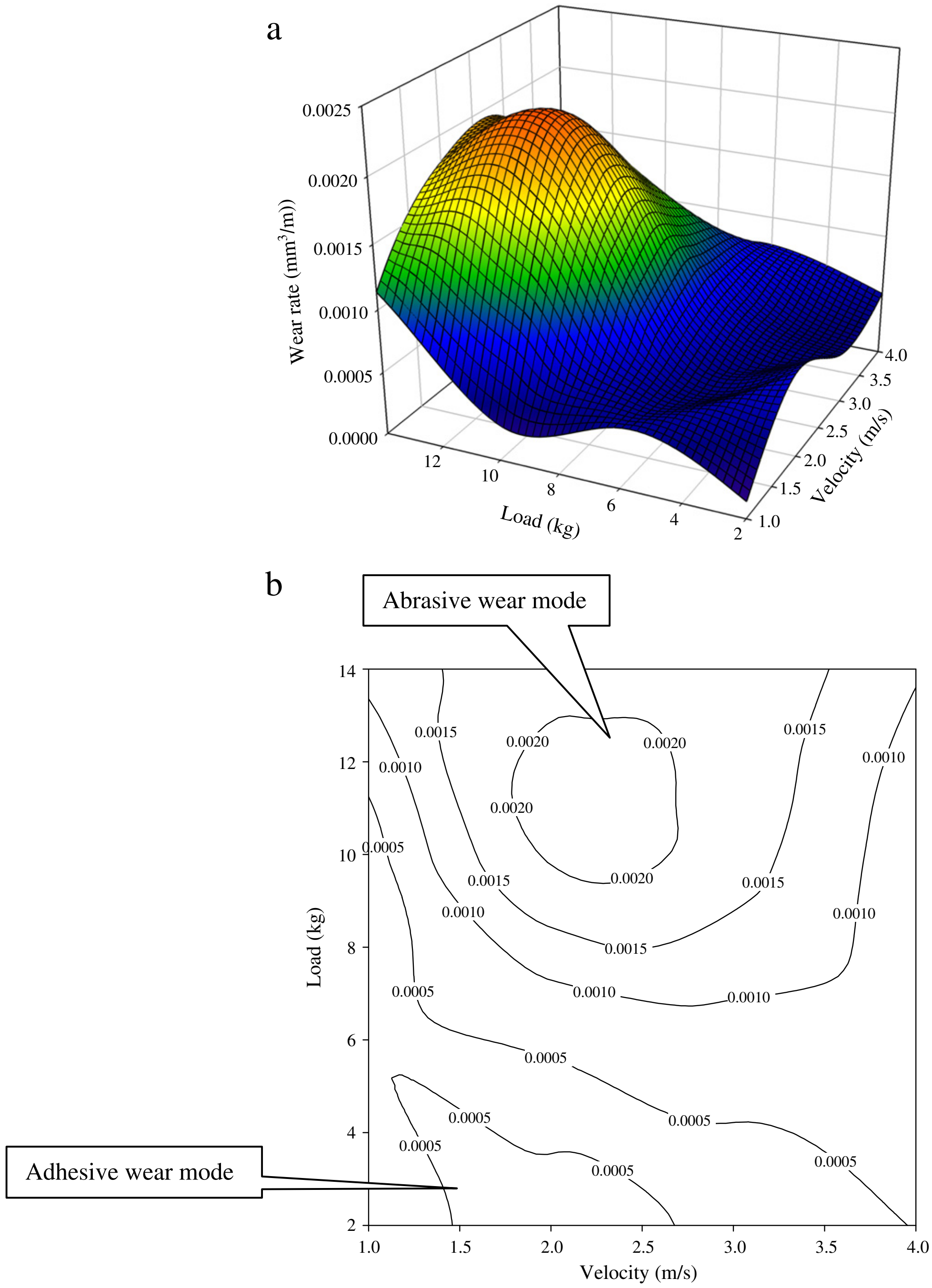

Fig. 5. 3D surface response for DCTs (a) and 2D contour (b).

and hence the loosening of the diamonds from the matrix. Thus dislodged diamond particles and broken pieces of diamonds form the part of mechanical mixed layer and hence accelerate the process of wear. In other words, the wear mechanism changes from two body wear as depicted by adhesive wear mode at low load to third body wear at higher load by abrasive wear mode (Fig. 6). Based on the above understanding, a schematic model for diamond particle pull-out/fracture is proposed as illustrated in Fig. 7.

Brief description of stages: [I] diamond particle embedded in the matrix; [II] diamond particle is just exposed due to wear loss of the surrounding matrix; [III] advanced stage at which the maximum portion of the particle is exposed to wear loss of the surrounding matrix; [IVa] diamond is dislodged due to weakening of particle–matrix interface leaving cavity; [IVb] diamond particle shows fracture due to nucleation of microcrack in the particle; and [IVc] one corner of the particle is thrown out in the direction of sliding (v) due to heavy tangential frictional forces.

4. Conclusions

The diamond cutting tools analyzed for wear test were studied for all the possible load and speed combinations. Based on the analysis, the following conclusions can be drawn,

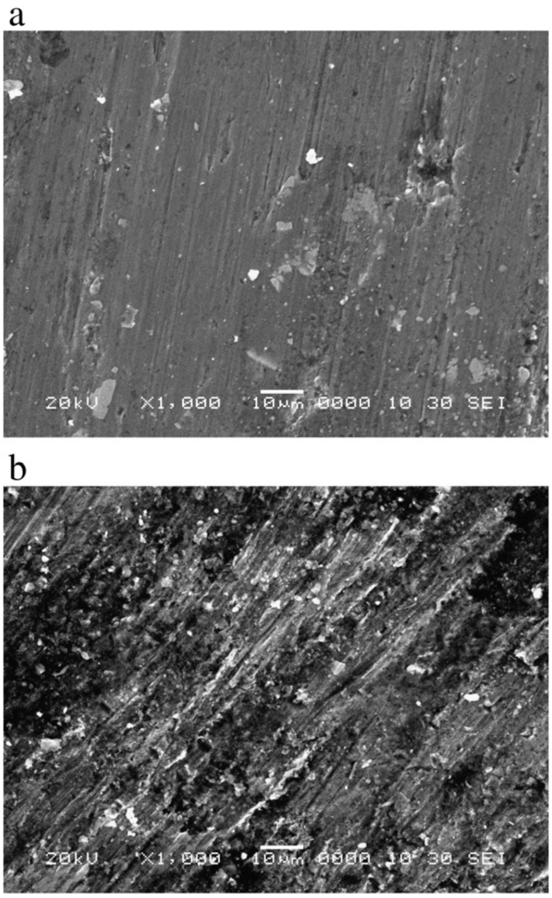

Fig. 6. SEM images of worn surfaces showing dominant adhesive wear mode (a) and abrasive wear mode (b).

a) The stability of diamonds at sintering temperature and its performance in dry sliding wear is established.
b) The 2D contour plotted delineates adhesive wear mode and abrasive wear mode in wear map. It means the DCTs can show satisfactory performance at low loads and low sliding speed.
c) The wear mechanism changes from two body wear to three body wear with simultaneous increase of load and sliding speed.
d) The loss of diamonds by way of fracturing and dislodgement during wear accelerates the process of wear has been investigated.

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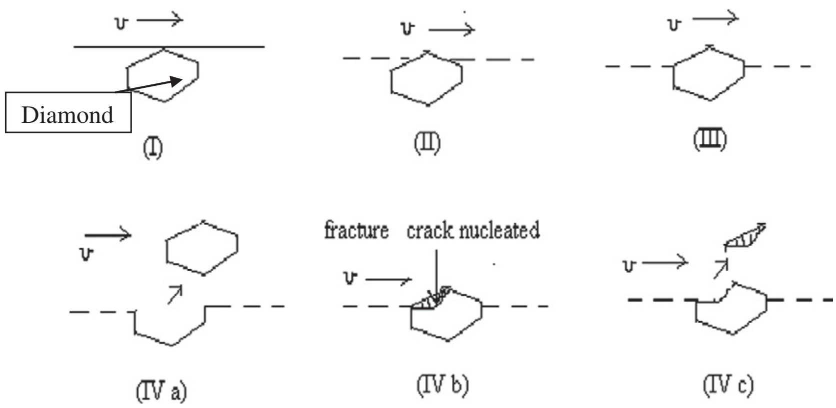

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Fig. 7. Model proposed for diamond particle pull-out/fracture mechanism in the wear of diamond cutting tool.