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Drilling studies of an Al_2O_3–Al metal matrix composite Part I *Drill Wear Characteristics*

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Comparative drilling studies have been carried out for a 20% Al_2O_3 microsphere reinforced Al metal matrix composite (MMC) using a (a) high speed steel (HSS) drill, (b) tungsten carbide (WC) drill and (c) polycrystalline diamond (PCD) drill. In this part of the paper, the flank wear characteristics of the drills have been presented. It is found that for the HSS drill a flank wear of 1.00 mm is reached in drilling for as little as 12 s. In contrast, under similar conditions for the WC drill, a flank wear of 0.16 mm was observed after drilling for a period of 600 s and in the case of the PCD drill, after 2210 s of drilling a flank wear of only 0.12 mm was observed. The PCD drill, however, showed some signs of chipping in the early stage, but this seemed to stabilize later on. Scanning electron microscopic (SEM) observations of the worn drill tips revealed that in addition to flank wear the HSS exhibited margin wear, the WC drill exhibited both margin wear and chisel edge wear and the PCD drill displayed crater wear.

1. Introduction

In comparison with unreinforced monolithic alloys and resin matrix composites, MMCs offer higher stiffness and strength values, lower coefficients of thermal expansion and the ability to be used at higher temperatures [1, 2]. MMCs also offer the ability of being tailor-made with specific properties for a particular application.

MMCs can be classified according to the type of reinforcement [3]. Continuously reinforced MMCs are those reinforced with long and continuous (unbroken) fibres with diameters greater than 100 μm and volume fractions, V_f, upto 70%. The second type of MMC is the discontinuously reinforced one, either by whiskers, platelets, nodules or particulates [3]. The particulates are usually equiaxed with equivalent diameter greater than 1 μm and a V_f between 5 and 40% [3, 4].

Particulate metal matrix composites (PMMC) are economically cheaper in both raw materials and fabrication processes and have potential for applications requiring relatively large volume production [3, 5]. The relative ease of fabrication of PMMCs is also another favourable factor. These can be produced via solid state (powder metallurgy), liquid metallurgy or metal spray methods [3]. All such processes are readily available for manufacturing unreinforced alloys [5]. In addition, the use of secondary processes, such as rolling, forging, extrusion and heat treatment, can be applied only to discontinuously reinforced composites [6] without incurring significant damage to the reinforcement.

A major problem faced by designers and MMC producers is in the machining of the components. Near-net shapes can be achieved by fabrication methods, such as squeeze casting and powder metallurgy, but due to the component design and quantity required, and the fact that MMCs require drilling, grinding and turning, then the machining operation cannot be totally eliminated [7].

Machining is a material removal process and therefore is critical in the final fabrication stage prior to application [8]. Unlike fabrication studies, there has not been much focus on the machining aspect of MMCs despite the fact that all composites fabricated require some machining for use in structural components [9].

Metals are homogeneous, whereas MMCs are not; the hard abrasive reinforcements contribute to the limited success of standard machining practice, causing high tool wear rates and significant damage to the work piece [10].

Drilling is the most common machining operation, since many holes must be drilled in order to install mechanical fasteners [11]. Poor hole quality accounts for an estimated 60% of all part rejection [12] and since holes are drilled in finished products, rejection of parts due to poor hole quality can prove very costly.

From an economical view point too, cost effective machining methods need to be developed and readily applied to MMCs, so as to reduce the total cost of each component and thus increase its competitiveness among other material systems [13].

Previous studies have indicated that the common HSS tool cannot be applied to MMCs, this is because of the excessive wear that occurs within a very short working period [4, 14–16]. WC tools should be limited to low volume fraction reinforcements and then only where short runs are required. These studies indicate that PCD tools need to be considered as they are advantageous in machining MMCs even in long run production environments. However, these studies do not consider any systematic measurements of the drilling forces and their correlation to the drill wear.

Natural diamond is the hardest of all known materials [17], but its high costs and limited availability of numbers suitable for industrial applications, have forced the development of a synthetic diamond industry.

PCDs were first developed by Wentorf and Rocco (1973) and these had a distinct advantage over single crystal diamond in that they were isotropic and lacked the presence of a single cleavage plane. However, their successful advancements in this technology have occurred only in the past five to ten years.

PCD can be defined as a conglomerate of randomly orientated synthetically produced diamond crystals, which are sintered together in a cobalt matrix to form "mother blanks" [18]. The cobalt is used to provide toughness, oxidation resistance and electrical conductivity which allows the electro discharge machining of the large mother blanks into smaller blanks or inserts [17, 19].

Cutting tools wear because (a) normal loads on the wear surfaces are high and (b) the cutting chips and work piece that apply these loads are moving rapidly over the wear surface [20]. The cutting action and the friction of the contact surfaces increase the temperature of the tool material, which further accelerates the physical and chemical processes associated with tool wear. These forces and motions are necessary for material removal and thus cutting tool wear is an inevitable production problem for manufacturing industries.

Cutting tool wear occurs along the cutting edge and on adjacent surfaces [20]. The location and size of these wear surfaces play an important role in determining the useful life of the cutting tool. Fig. 1 shows the characteristic appearance of a worn twist drill [21].

Drill performance is traditionally determined by failure of the drill [21]. In a given drilling operation, the performance criterion should be governed by the drill life, expressed as the number of holes to failure or equivalent time of drilling. Failure in drilling is usually defined either by a suddenly appearing violent noise or by catastrophic fracture of the drill.

Adhesive and abrasive wear are the most commonly encountered mechanisms in machining operations [22]. A particular wear mechanism is dependent upon
1. the contact stress,
2. relative velocities at the wear interface,
3. temperature, and
4. the physical properties of the material in contact [20].

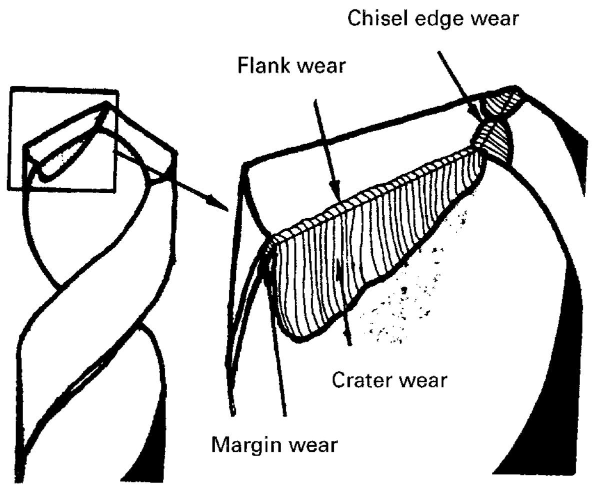

Figure 1 Characteristics of a worn twist drill [21].

TABLE I Vickers hardness values of various ceramics and cutting tool materials [25]

Cutting tool	Vickers hardness
PCD	8000
TiC	3000
SiC	2400
Al_2O_3	2100
WC	1900
HSS	857[a]

[a]Hardness value measured by authors.

In composite materials the tool wear rate also depends on the volume fraction and the type of ceramic particles, the type of matrix and the heat treatment condition [14].

Abrasion is the primary mode of tool wear when drilling PMMCs, as the cutting edge of the tool encounters the reinforcing particles in the aluminium [14]. These hard particles chip away tiny flakes of the tool edge, be it of carbide or PCD. Abrasive wear involves the removal of tool material by a scoring action of hard phase inclusions in the chip [23].

Machining experiments with materials of known microstructures have shown a correlation between increased tool wear and increased amounts of abrasive particles in the work material [24]. Brun *et al.* [16] suggest that the key property required for a cutting tool material in order to successfully machine a high volume PMMC is a hardness greater than that of the reinforcing phase. Diamond has the highest hardness of cutting tools, hence is the most suited tool material from this point of view. Table I shows Vickers hardness values of common cutting tool materials [25].

For PCDs it is observed generally that those made from the finest diamond aggregates, and thus having a finer grain structure wear more easily than those of the coarser grained tools [19]. Consequently the coarser tools are more commonly used for rough machining, while the finer grained PCDs are used in a later stage where high surface finishes are required.

Another important consideration in abrasive wear is the area and time of contact between the cutting tool and the work piece material [25]. Assuming that a unit volume of material is to be removed, the area swept by the cutting edge is the product of the width of cut and feed rate. For a given width and depth of cut, the contact area between the tool and work piece is proportional to the feed rate. This is the basis of rough machining in that the use of high feed rates produce maximum material removal and minimum tool wear.

The increase in surface roughness (as the total depth of drilling increases) is due to the generation of narrow grooves on the work piece. As the cutting depth increases, the cutting temperature increases and this may cause the binding between the reinforcement and the matrix to weaken, thus the matrix softens. When the tool edge comes in contact with the hard reinforcing particles it tends to move them rather than cut them, thus the particles are making grooves on the surface of the work piece.

Lane [26] suggests that the determining factor in drill life is not governed by the flank wear of the cutting edge, but by the hole quality produced. Given that holes are drilled in the final product prior to assembly, then holes must be of a certain diameter, of the desired roundness and straightness. These features are critical in that poor hole and surface quality may act as stress raisers and result in poor affixation of the structure. Scrap amounts and further work, such as reaming operations, can be eliminated, and thus total costs reduced if these hole characteristics are achieved through the use of proper tool materials, proper feed rates and cutting speeds, coolants and working parameters.

The present work examines the wear behaviour of HSS, WC and PCD tools in machining an Al_2O_3 reinforced Al alloy PMMC, and seeks to establish a correlation between the flank wear and the measured forces (thrust and torque). In addition, performance comparisons have been made in terms of total holes per tool, hole and chip quality and the relative work done by the cutting machine for each type of tool. The overall drilling efficiency has also been examined.

Part I of the work will present results on the drill wear characteristics, and Part II will discuss the force characteristics and surface quality of the drilled holes.

2. Experimental procedure

The PMMC used in this work is Comral 85™ (Comalco microsphere reinforced aluminium) in the form of extruded bars, 75 mm in width and 25 mm in height. Six drilling blocks were cut, each with a length of 112 mm, using a Struers Exotom automatic cut-off abrasive wheel. Comral 85 is produced by the liquid metallurgy route through the addition of ceramic microsphere particulates to liquid aluminium 6061 alloy [27, 28]. Comral consists of an aluminium alloy matrix of composition 0.8–1.2% Mg–0.4–0.8% Si or 7% Si–0.3–0.6% Mg and the rest is aluminium (Al).

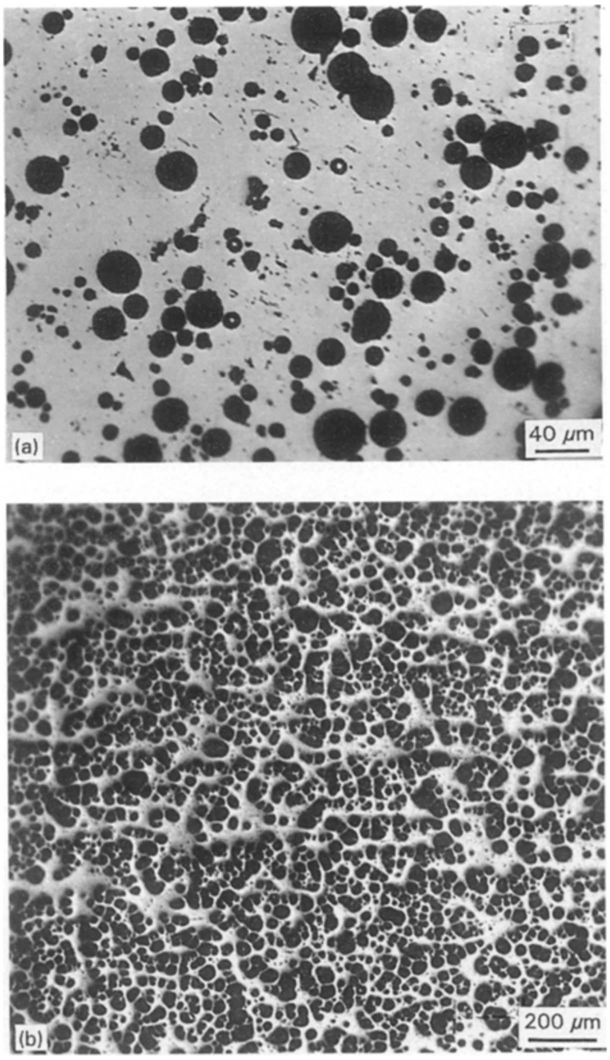

Figure 2 Comral 85 in (a) transverse and (b) longitudinal directions.

The spherical reinforcements (Micral, microsphere alumina) are polycrystalline, fine grained and with a size range of 1–40 μm (average size of 20 μm) and a volume fraction of 20% [28]. Micral contains mainly two phases, mullite ($3Al_2O_3.2SiO_2$) and corundum (α-Al_2O_3). Fig. 2 shows the particle distribution in the direction of extrusion, as well as perpendicular to this direction.

By use of an image analysis programme, and with 12 samples the volume fraction of reinforcing particulates was found to be somewhat non-uniform in the matrix, having an average volume fraction of 26% (range 23–28%).

The drilling blocks were solution treated at 530 °C then artificially aged to peak hardness (determined from previous work [8, 29–31]) at 175 °C for 8 h in a muffle furnace. It was aimed to achieve a uniform hardness value between the drilling blocks, such that the blocks would not differ greatly in hardness. The six drilling blocks were found to possess a very consistent Vickers hardness number of 137, with a spread of ± 3 VHN.

The drills used in this study were
1. HSS of the P&N type,
2. WC tipped on a Nachi HSS body and

3. PCD tipped (DeBeers Syndite range, grade 010) on a P&N HSS body.

For the PCD tipped drill the drill diameter was 8.0 mm, although the PCD cutting diameter was 8.1 mm. The brazing of the PCD tip to the HSS body was done by a commercial tool working firm.

The drilling operation was performed using Prvomjska universal milling machine with a drill head and a specially prepared mounting block for specimen housing. A four component Kistler type dynamometer was used, whose leads were connected to a four pen chart recorder. The three orthogonal, x, y and z, (thrust) forces and the torque, M, were measured as outputs for each drilling operation. (A schematic diagram of the dynamometer assembly will be shown in Part II).

Drilling was carried out at a preselected speed (1800 r.p.m.) and at a constant feed rate (110 mm min^{-1}) for all the drilling operations, blind holes were drilled to a depth of 20 mm, and a Hocut B60 coolant was used at all times. A total of 40 holes per block were drilled, a wall thickness of 5 mm between drilled holes was used. Drilling time for each hole was approximately 12 s. (It is recognized that the three different drills, if used on their own, may need to be used at different speeds; however, for a comparative study it was necessary to keep these the same.)

The flank wear on both cutting lips of the drill (arbitrarily designated flank A and flank B) was measured by use of a Nikon Measurescope, where maximum flank wear values were recorded. It is believed that catastrophic failure of a drill would depend on the maximum flank wear, so this was selected as the parameter of measurement, rather than the average wear.

Photographs of the drill tip were taken prior to use and then taken at regular intervals. A Zeiss tessovar photomacrographic zoom system and a mounted 35 mm camera were used for this.

SEM observations were carried out on a Joel JXA-840 microscope. For this purpose it is necessary to coat the MMC with carbon because the alumina particles are non-conducting and otherwise become charged.

The drill tips were cut at the end of the drilling experiments and then studied in the SEM, to examine the wear mechanisms acting on the drill tips.

3. Results and discussion

3.1. Drilling observations

3.1.1. Flank wear

Forty holes were drilled per drilling block, Table II showing the number of holes drilled per drill type, the time per hole and the maximum flank wear measured after the final hole.

The results of flank wear versus holes for HSS and WC can be seen in Fig. 3. It can be seen from Fig. 3 that the flank wear is initially small when the tip is sharp, but as drilling continues the flank wear increases. This trend seems to be linear.

Figs 4 and 5 show the state of the flank wear at various points in the tool life for HSS and WC, respectively, i.e.

TABLE II Total holes drilled and maximum measurable flank wear[a]

Drill type	No. of holes	Flank wear (mm)	Time per hole (s)
HSS (drill No.1)	1	1.00	12
HSS (drill No.2)	1	1.05	12
WC	50	0.16	12
PCD	184	0.12	12

[a]Depth of a full hole = 20 mm.

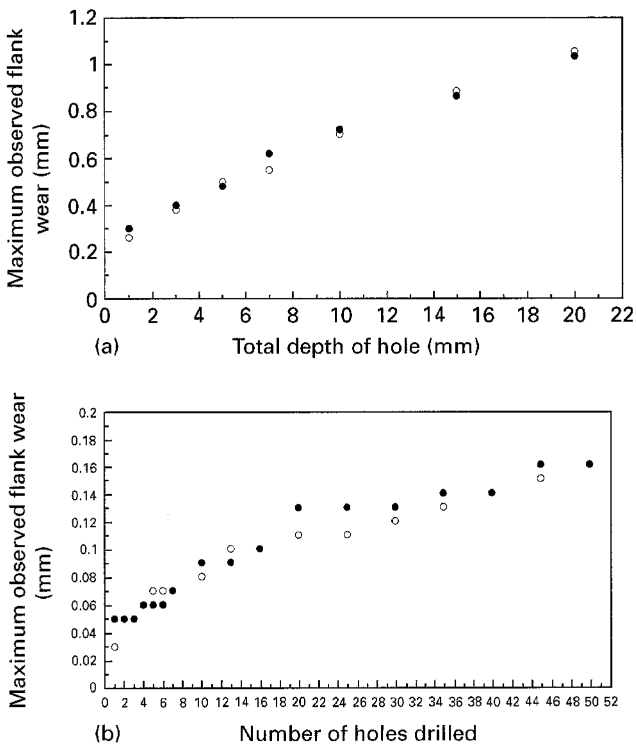

Figure 3 Flank wear measurements for (a) HSS, and (b) WC tools:(○) flank A, (●) flank B.

1. prior to drilling,
2. after hole one, and
3. the middle and final holes drilled.

From these figures it can be observed that the Al_2O_3 (in the composite), which is harder than both HSS and WC, abrades away the flank with each cut. It can also be seen that maximum wear takes place at the outer edges of the tip and minimum wear occurs at or near the point of the tip. This is because the maximum rotational force and the maximum tip-to-workpiece contact occur further away from the point and thus the point is abraded away more quickly, whereas at the "point" itself little rotational force is experienced by the tip and the force is more like "pushing" into the work piece rather than cutting.

Initial observations of the as-received PCD tipped drill (which had an initial diameter of 8.6 mm) revealed a very jagged and uneven rough cutting edge, with chipping upto 0.05 mm visible. There was evidence of imperfect brazing and unfinished grinding. After drilling one hole the chipping became excessive and the drilling operation was terminated. The produced hole was of poor quality, having uneven

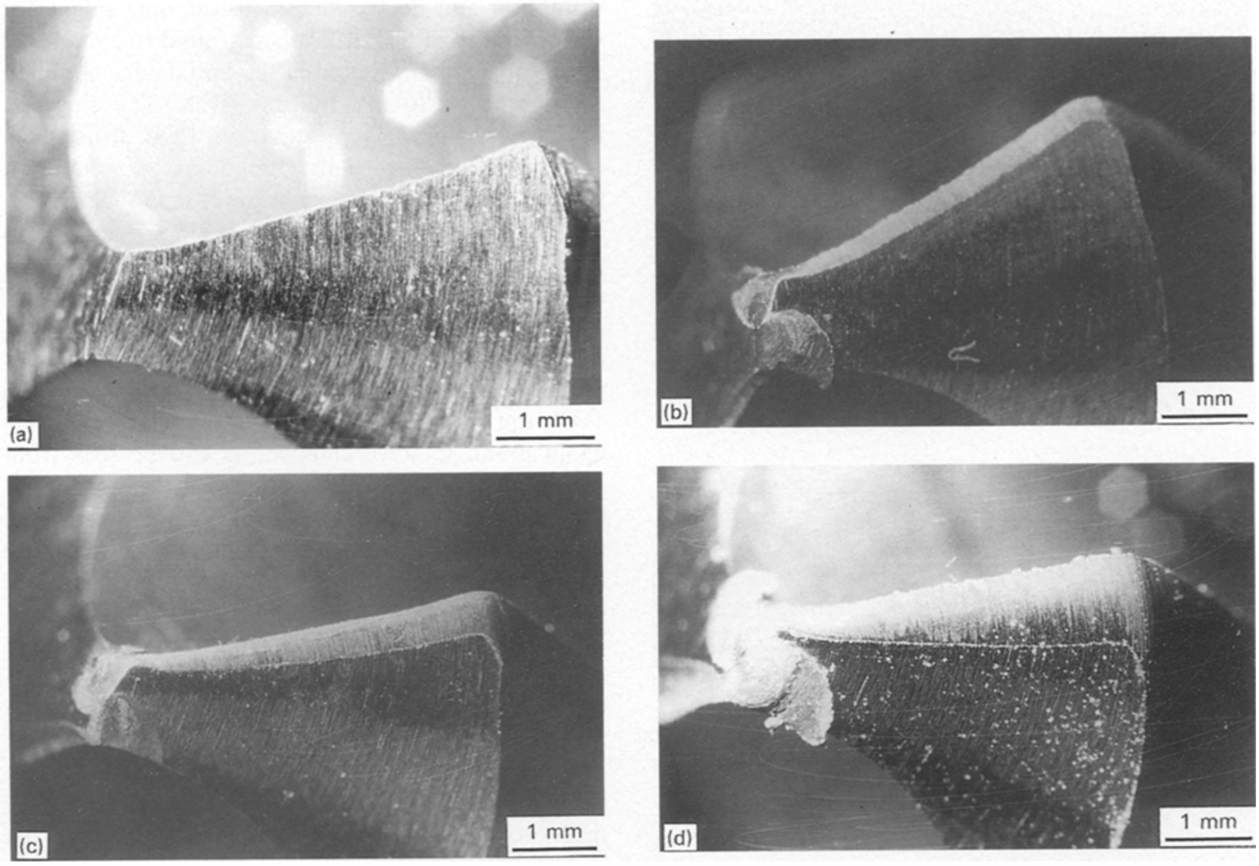

Figure 4 HSS flank wear after (a) 0, (b) 1, (c) 5, and (d) 20 mm hole depth.

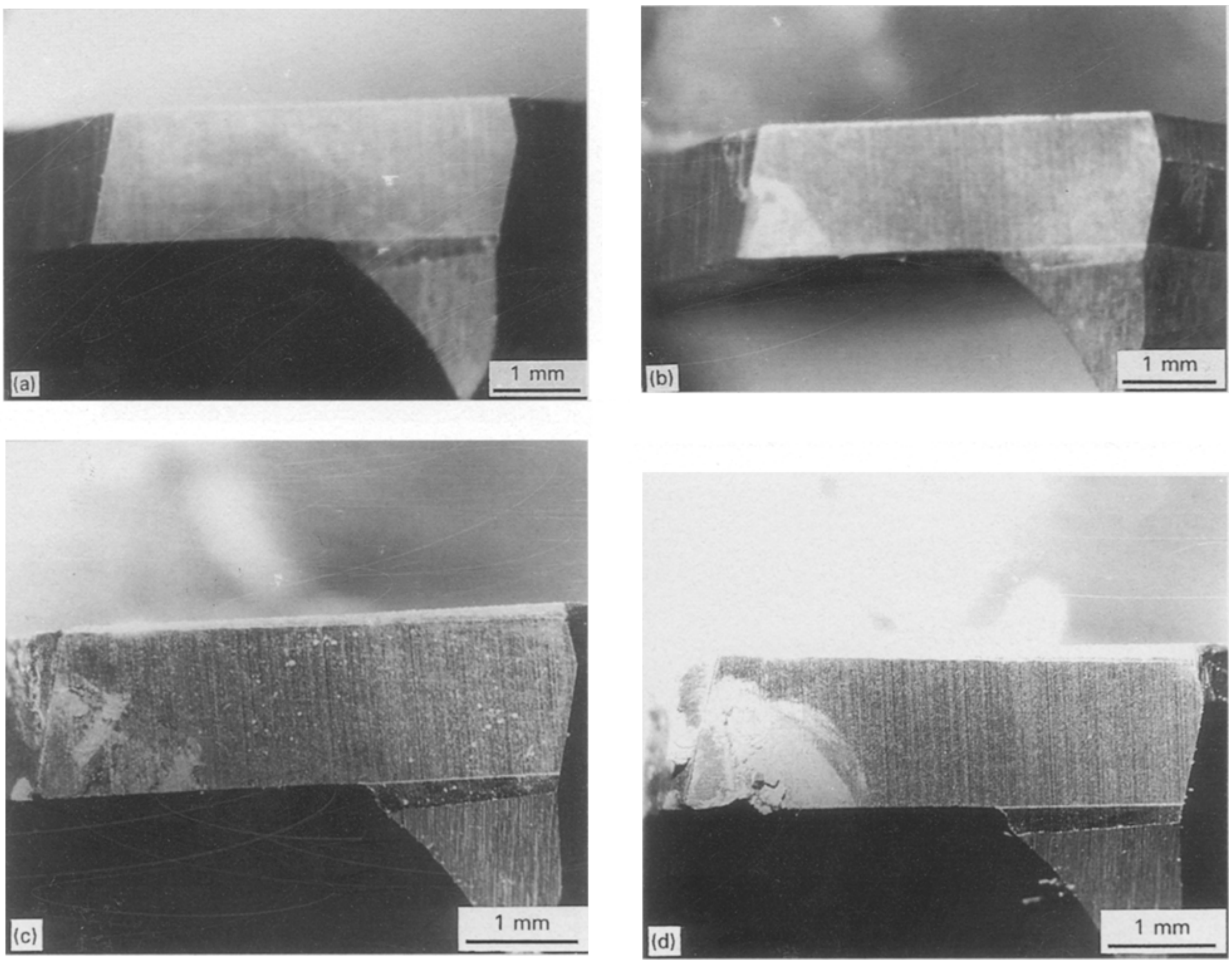

Figure 5 WC flank wear after (a) hole 0, (b) hole 1, (c) hole 25, and (d) hole 50.

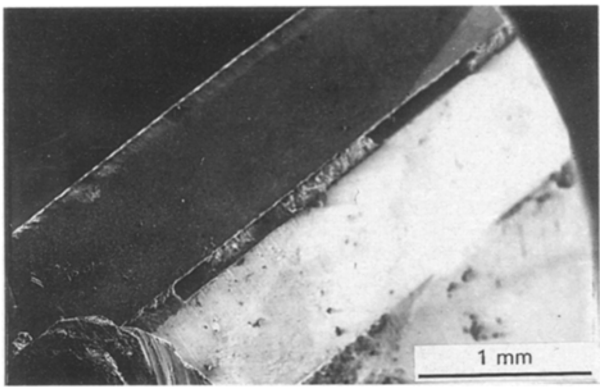

Figure 6 Poor brazing between PCD and WC substrate layer.

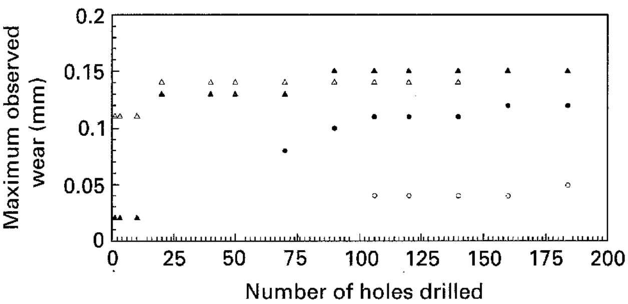

Figure 7 PCD chipping and flank wear measurements:(△) maximum chip flank A, (▲) maximum chip flank B, (○) flank A, (●) flank B.

roundness and no parallelism of the hole sides. For this reason the PCD drill was reground to a diameter of 8.1 mm, which resulted in the initial edge chipping to be reduced to insignificant levels. The chipping problem is somewhat expected with PCD drills and is attributed to the poor toughness of diamond ($K_{1c} = 8.81$ MPa m$^{0.5}$), which is lower than that of both WC ($K_{1c} = 10.8$ MPa m$^{0.5}$)[32] and HSS. (The brazing problem was not completely fixed, however, still leaving a gap between the PCD layer and the carbide substrate, which can be seen in Fig. 6. However, this did not seem to significantly affect the drilling studies undertaken.

During the first drilling operation the PCD tip was again found to have chipped, as can be seen from Fig. 7, reaching a maximum depth of 0.11 mm after hole one, then increasing to 0.14 at hole number 20. However, following this point there was no more chipping. In Fig. 7 one can see that upto the twentieth hole the depth of chipping was significantly different between flank A and flank B, with flank A sustaining the bulk of the chipping. This may perhaps be attributed to different grinding angles and an uneven surface finish.

Measurable flank wear of the PCD drill did not occur until hole 70, again there was a significant difference in flank wear between the two lips of the drill, with flank B sustaining the greater wear (and

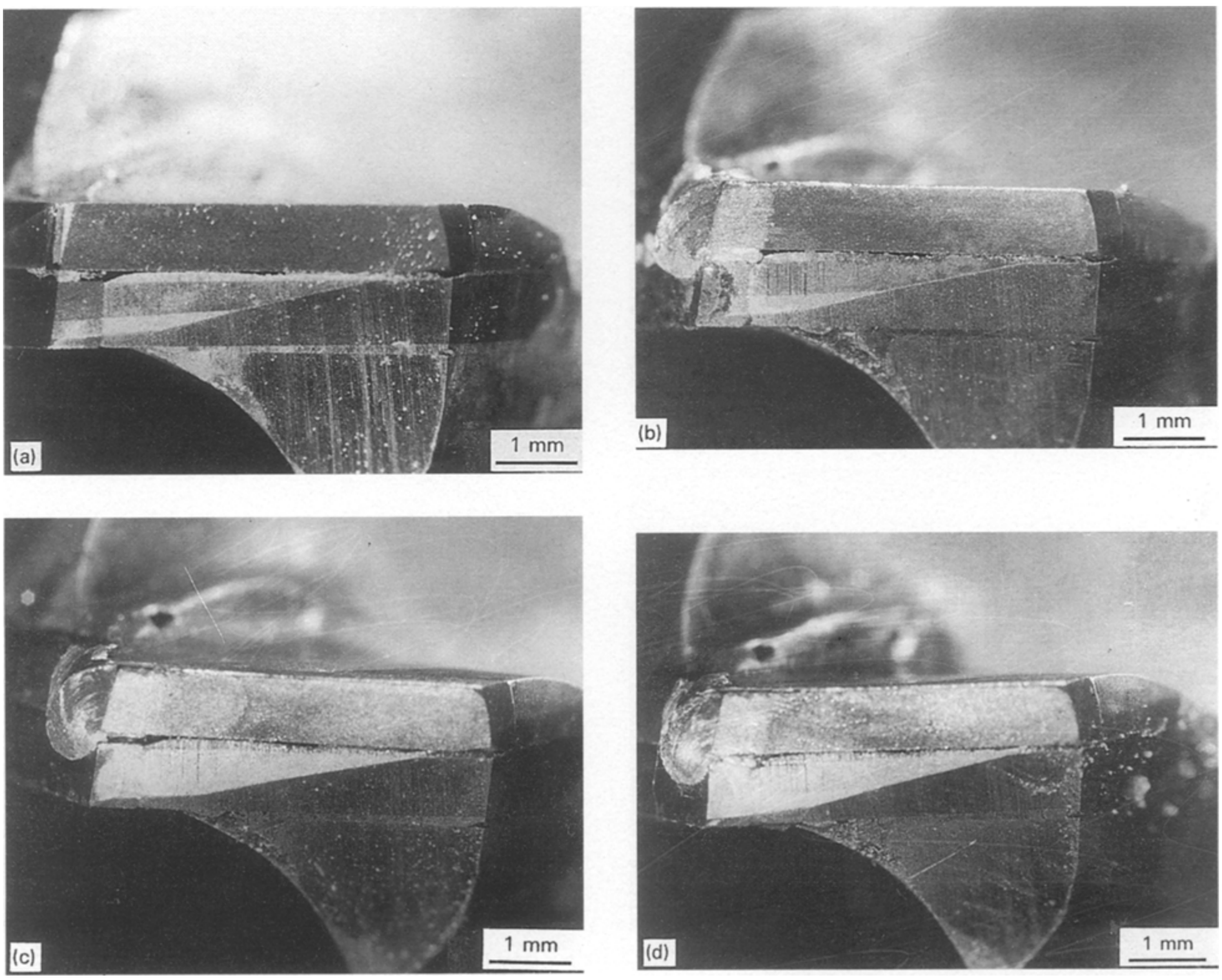

Figure 8 PCD flank wear at (a) hole 0, (b) hole 50, (c) hole 106, and (d) hole 184.

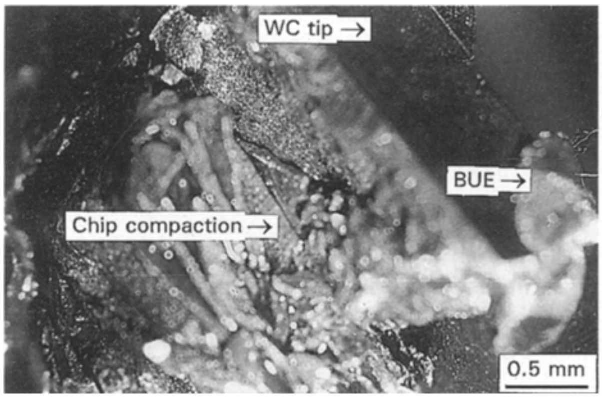

Figure 9 Chip compaction observed on WC tool.

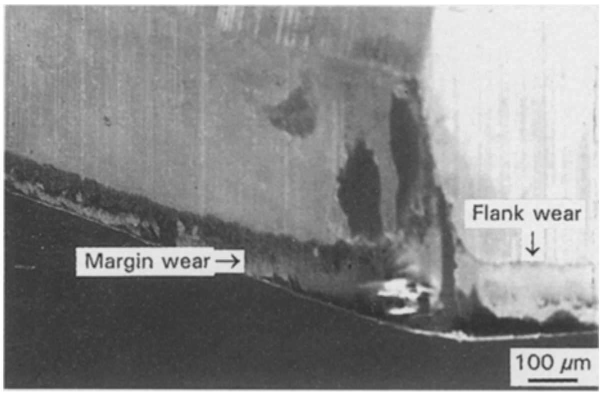

Figure 10 Margin wear as observed on the WC drill tip.

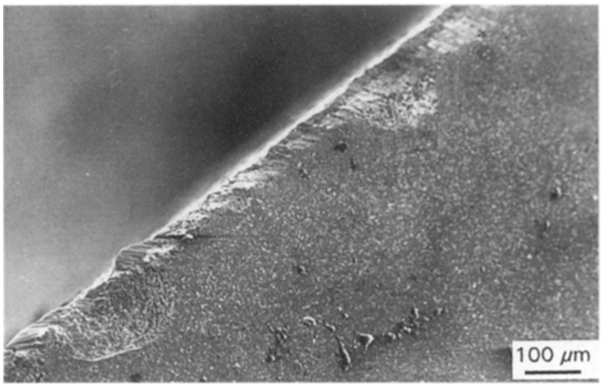

Figure 11 Chipping on PCD cutting edge.

lesser chipping); suggesting that flank B is cutting through the material and is thus wearing, where as flank A is forcing its way into the material.

The PCD flank wear was observed to increase very slowly (Figs 7 and 8), as could be expected since PCD is harder than the alumina particles. For example, the wear increase between hole 70 and hole 184 was approximately 0.04 mm, whereas the total wear sustained by the WC drill in the experimental time of 50 holes was 0.16 mm. As with the WC and HSS tools, maximum flank wear in the PCD tool was observed to be furthest away from the point, and maximum chipping occurred near the point of the tip.

The cutting chips' characteristics as observed are given below. PCD gave the best chip ejection and best chip size and uniformity, the WC drill was removing chips well upto the tenth hole when the problem of

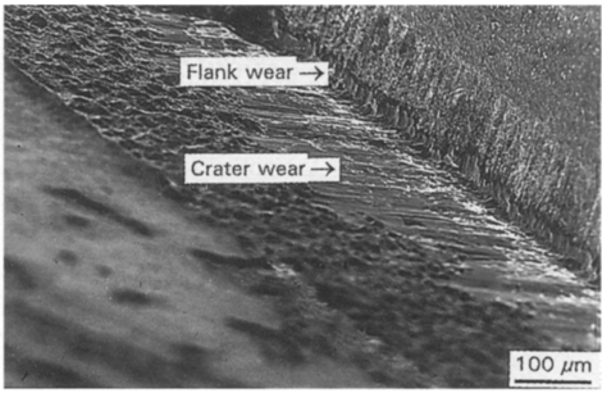

Figure 12 Flank and crater wear on PCD cutting edge.

chip compaction on the flutes and at the tip became evident and pronounced (Fig. 9). For the WC drill manual chip removal was required by means of mechanical force or by a pressurized air stream, after frequent intervals to avoid premature drill failure. (Chip compaction causes the "choking" of the drill and causes an increase in the thrust force applied and an increase in measured torque.)

The formation of a built up edge (BUE) on the tip of the tool was more pronounced for WC than PCD drill. BUEs were readily formed on the WC tip, but were found not to form on the PCD tip. The BUE required the use of mechanical force for removal. BUE is one of the major sources of surface roughness and it also plays an important role in tool wear. BUE actually protects the tip from chisel edge wear, but the formation of the BUE is not by itself advantageous as it promotes uneven wear between the flanks, and it increases the surface roughness as well as the associated drilling forces.

A problem with the PCD tool was the accumulation of aluminium in the crevices or gaps left behind by the poor brazing, although these did not seem to influence the wear behaviour (or recorded forces).

3.1.2. Wear mechanisms

Other than flank wear, which was observed in all drill types, there were other types of wear observed in the drills under the SEM. These are described below.

For both the HSS and WC drills margin wear was observed; Fig. 10 showing the margin wear present on the WC tip. As with flank wear, margin wear is greatest at the edge furthest away from the point and it then uniformly decreases. Margin wear is attributed to the rubbing action between the drill tip sides and the hole surface resulting in increased thrust and torque forces and in greater surface roughness. For the PCD no margin wear was observed, suggesting that there is a large enough clearance angle so that little or no interaction occurs between the drill tip sides and the hole.

Chisel edge wear was not observed in the HSS or PCD tools, but its presence in WC drill was obscured by a heavy BUE layer (Fig. 5d), although certain areas of the WC tip showed signs of chisel edge wear.

Two observed characteristics of the PCD drill were chipping and crater wear, as seen in figs 11 and 12, respectively, which were not evident in either the HSS or WC tools. Chipping is presumably due to the poor toughness of diamond, while crater formation is a characteristic of diffusion wear and is attributed to the greater severity due to the chips rubbing on the tool face.

4. Conclusions

1. HSS flank wear was greater than 1.00 mm after only 12 s (or one hole) of drilling.
2. WC flank wear of 0.16 mm was observed after 600 s (or 50 holes) of drilling.
3. PCD flank wear of 0.12 mm was seen after 2210 s (or 184 holes) of drilling.
4. WC drill resulted in cutting chip compaction requiring manual removal of chips from the drill flutes and also from the hole and thus resulted in drilling delays.
5. The PCD drill showed excessive chipping during the initial drilling periods, which then stabilized.
6. Beginning of PCD flank wear was observed only after hole number 70 and was found to increase only marginally thereafter.
7. Further improvements in PCD fabrication, brazing and grinding is recommended to avoid chipping and delays.
8. Other than flank wear, the HSS and WC drills exhibited margin wear, the WC also exhibited signs of chisel edge wear although this was obscured and protected by a heavy BUE layer. The PCD drill on the other hand exhibited only crater wear.

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