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Material removal by spalling during EDM of ceramics

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Abstract

This paper introduces the concept of a rapid rough-machining regime for die-sink electrical discharge machining (EDM) of advanced ceramics, offering potentially high rates of material removal and improved process efficiency. Whereas the conventional material removal mechanisms of spark erosion involve melting, dissociation and evaporation, the authors have established that prolonged high-energy discharges (in this paper as arc-related discharges) promote areas of spalling in which surface layers of ceramic material are released as large flakes by thermal-shock induced fracture. This paper describes tests on sialon–TiN and SiC–TiB_2 composites. No catastrophic fracture of these materials was observed under arcing conditions, clearly demonstrating their robustness. Flakes of material typically up to several hundred microns across and one hundred microns thickness were isolated from captured debris, often segmented by vertical cracking. Sectioning of the eroded work-piece revealed shallow sub-surface cracking which ran parallel to the machined surface, typically following its profile at near-constant depth and which usually limited the extent of vertical cracking to the layer of material above. Subject to optimising electrode pulsation and delivering controlled, randomly distributed high energy discharges, this regime offers the potential for a reliable and fast "fissile planing" technique in which material is removed in shallow layers.

Keywords: Composites; Machining; Sialon–TiN; SiC–TiB_2; Spalling

1. Introduction

The two principal mechanisms of material removal which may occur during spark erosion of ceramic materials are either melting, evaporation and dissociation, or fracture-related spalling, depending on the material's properties and electrical discharge machining (EDM) parameters imposed. The former is the most common and universally accepted erosion mechanism, and that which has been most widely researched and theoretically modelled.[1,2]

This current research, however, has established that if the heat delivery during electrical discharge is sufficiently intense, large scale spalling can be induced to provide a more rapid and more efficient EDM machining regime for ceramics based on thermal shock induced fracture.[3] The amount of energy required to generate sub-surface cracks and remove material from the surface by flake detachment is clearly less than that required to remove material more directly through the mechanisms of melting, evaporation or dissociation making material removal through controlled spalling an attractive proposition.

Ceramic composites designed for EDM usually incorporate an electrically conductive particulate dispersion to increase conductivity. Improved fracture toughness and densification may occur as a result of dispersoid addition.[4] Good homogeneity is required for spark erosion,[5] more recently achieved through in-situ reaction sintering[6] rather than direct powder addition.

Particulate compositions in which thermal expansion mismatch exists between constituents, however, must be more susceptible to spalling owing to the increased stress concentrations at the boundaries between dispersoid particles and surrounding matrix. Dispersoid particles are therefore likely to act as nucleating points of crack initiation where the resultant stress concentrations exceed the tensile strength of the material locally, making these specialised materials ideal candidates to utilise spalling as an effective material removal technique.

The stress distribution which gave rise to spalling when a single phase ceramic was subjected to a localised

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hot spot was predicted by Tvergaard et al.[7] Their analysis showed the existence of conflicting compressive and tensile stresses on planes both parallel and perpendicular to the surface during the intense temperature increase and subsequent temperature diffusion into the material. This temperature inversion is likely to be more intense for EDM machining as a hot-spot from an electrical discharge is immediately quenched by cooling dielectric fluid, increasing the severity of the stress differential and therefore the likelihood of crack generation.

Gadalla[8] machined pure polycrystalline TiB_2 by EDM and noted that the mechanism of material removal was predominately by cleavage of flakes of similar sizes to grain size, roughly 5 μm wide and 5 μm thick. The current authors have observed a similar result, though on two orders of magnitude larger scale, can occur from large energy releases in the form of arc discharges.

This work has revealed in both SiC–TiB_2 and sialon–TiN composites the existence of perpendicular and horizontal sub-surface cracks which ran near-parallel to the spark eroded surface after machining by EDM under arcing conditions. A spalling crack nucleated roughly parallel to the surface in the vicinity of the peak tensile stress is predicted by Tvergaard's analysis to spread outwards as a penny shaped crack, curving in response to the non-uniform stress distribution, but running more or less parallel to the surface. Conclusive confirmation of penny cracking was indeed discovered during this current research to occur during the EDM process.

2. Experimental

In order to study the material removal mechanism of spalling by EDM, two ceramic compositions were studied, namely:

- SiC–TiB_2 (7% vol TiB_2)
- sialon–TiN (30% vol TiN)

each with a particulate secondary conductive phase of higher thermal expansion coefficient than the surrounding matrix, as shown in Table 1.

Table 1
Coefficients of thermal expansion for ceramic compounds used

Ceramic compound	Coefficient of thermal expansion (K^{-1})
SiC matrix	4.3×10^{-6}
TiB_2	8.1×10^{-6}
Sialon matrix	3.0×10^{-6}
TiN	8.0×10^{-6}

Machining conditions which deliberately promoted arcing, namely no flushing and a short pulse-interval in relation to the pulse-length, were selected for a Charmilles Roboform 100 CNC die-sink electrical discharge machine. The current authors have identified these thermally intense arc-discharges as imparting a sufficiently major thermal shock (or succession of thermal shocks) to induce material detachment by spalling within some ceramic materials through the initiation and propagation of characteristic sub-surface fractures.

A typical area of material detachment on the surface of the SiC–TiB_2 composition caused by the spalling mechanism is shown in Fig. 1.

All of the debris released by spalling was captured for analysis using the simple apparatus shown in Fig. 2. Each material sample was spark eroded in a small isolated tank of static, fresh pre-filtered dielectric and the accumulated debris was subsequently separated by filtration.

Flushing was switched off throughout the machining period eliminating any possibility of external contamination and providing favourable conditions for the occurrence of arcing. Each machining test was for a

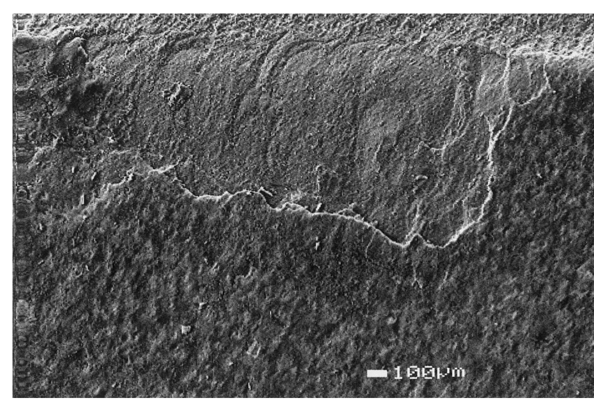

Fig. 1. Area of spalling on SiC–TiB_2 (7% vol TiB_2) after occurrence of arcing. Note: development of radial cracks and striations.

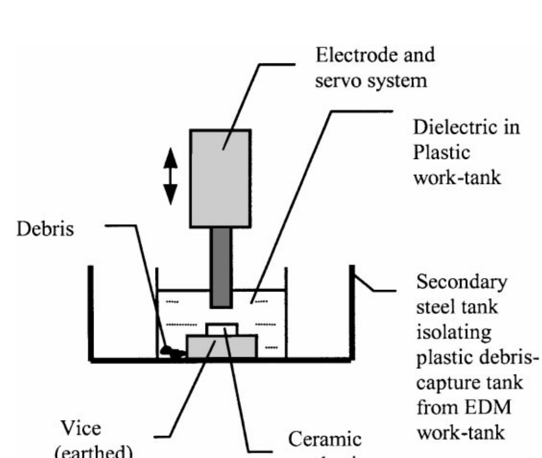

Fig. 2. Debris capture apparatus.

period of several minutes only to prevent overheating of the small volume of dielectric.

After machining, the spent dielectric was filtered leaving an oily residue deposit. This was gently heated to evaporate the liquid constituent, leaving a dried and cracked layer of residue crust on the filter slide with many released particles protruding above the surface-ideally situated for examination by scanning electron microscope (SEM), as shown in Fig. 3.

In order to establish the impact of sparking and arcing on the material immediately beneath the machined surface, the work-pieces were sectioned where appropriate by EDM using very gentle machining parameters, avoiding the risk of possible damage associated with mechanical slitting. After mounting in cold resin, the samples were progressively polished using diamond impregnated cloth discs to a finish of 6 μm.

3. Results and discussion

Examination of the accumulated debris after spark eroding the least electrically conductive SiC–TiB_2 composition using parameters which encouraged sporadic arcing yielded an abundance of small tabular particles, typically less than 50 μm across.

A singular large flake of debris, however, over 2 mm in length and detached from the parent material by subsurface horizontal cracking was captured intact. The upper surface of this flake, covered in a layer of recast material, is shown in Fig. 4.

Examination of the underside surface (shown in Fig. 5) revealed extensive vertical cracking which ran through the flake, segmenting and subdividing it into smaller fragments, but which did not always extend to the upper surface. This indicates that both vertical and horizontal cracks almost certainly originated below the surface of the parent material before the flake became detached.

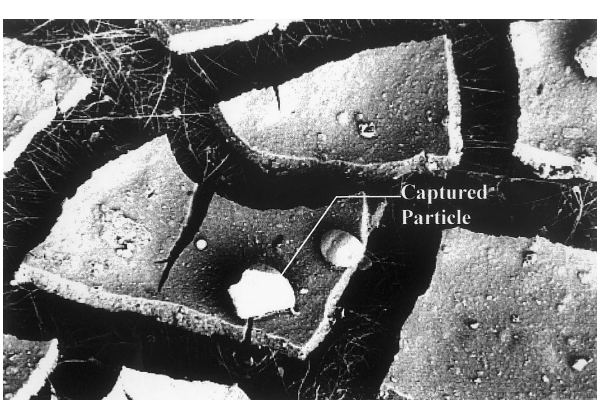

Fig. 3. Dried residue from EDM of SiC–TiB_2 composite. Captured particles are easily visible protruding above the surface (magnification ×150).

It is likely that a flake of this magnitude was initially released as a result of a localised multiple discharge event or arcing, and was only able to escape intact from the violent conditions of the spark gap because of the long periods of electrode retraction deliberately selected to take place between short periods of electrical discharge.

Under normal periods of electrode retraction, it is likely that such a large flake would have remained trapped within the confines of the spark gap and quickly disintegrated upon further spark bombardment. Smaller fragments of the original flake would then be released independently at a later stage by the explosive action of further sparking and the partial dielectric flushing effect induced by the vertically oscillating electrode.

Of particular interest on the spark eroded surface of the work-piece was a large flake of material in the final stages of detachment which was gently removed using an adhesive pad. This gave a unique insight into the spalling process by revealing both the fracture surface on the underside of the flake and the corresponding fracture surface freshly exposed on the parent material,

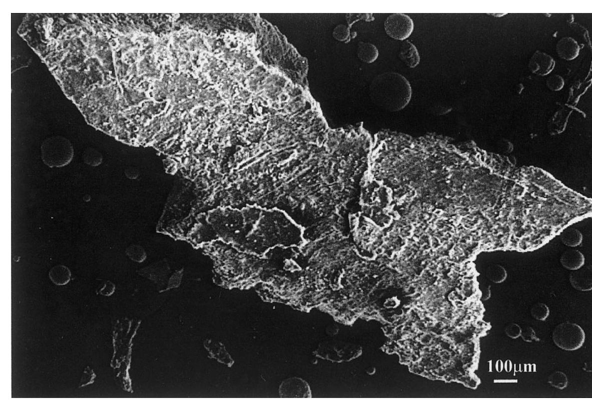

Fig. 4. Upper surface of large flake of SiC–TiB_2 (7% vol) composite detatched during spark erosion.

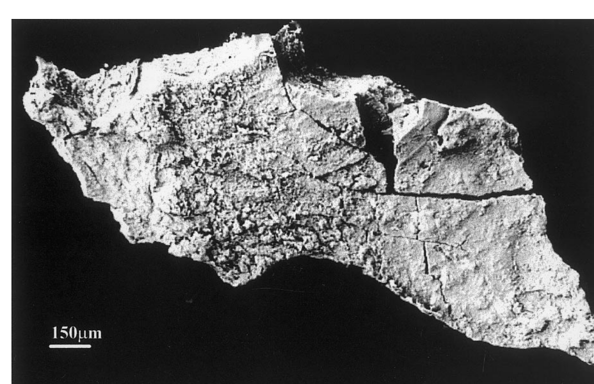

Fig. 5. Part of underside surface showing near-vertical cracks segmenting the flake.

shown in Fig. 6. This surface would normally be destroyed by further spark bombardment immediately after the flake had become dislodged.

Potential flakes of material up to several hundred microns across, defined by vertical cracking, were observed along the leading edges of the spalled area. These peripheral edges, shown in Fig. 7, had an overhung appearance where horizontal cracking undermined the surface layer as it progressed into the material.

Examination of the freshly exposed surface on the parent material revealed curved protruding edges indicative of propagating crack fronts running outwards from a central region within the spall area. These were mirrored on the under-surface of the detached flake.

On both the flake under-surface and corresponding exposed upper-surface of the parent-material, individual protruding particles of TiB_2 were clearly visible embedded in the material. Holes of similar size (generally less than 10 μm diameter) were also in evidence on both surfaces, most likely formed by the removal of these particles. Fig. 8 shows protruding particles of TiB_2 and vacant holes where TiB_2 particles once resided on the under-surface of the removed flake.

Under the higher magnification and greater depth of field of the scanning electron microscope, striations similar to beach marks were identified on the fracture surface running along the length of the flake. This beach-marking, seen in Figs. 1 and 8, provided clear evidence of cracks propagating under the punctuated thermal loading of successive arcing and sparking on the machined surface above.

It was often the case that protruding particles of TiB_2, or holes where such particles were once embedded, were located at the centre of flat bottomed penny-shaped cracks, examples of which are shown in Fig. 1 and highlighted in Figs. 9 and 10.

These shallow cracks possessed curved crack fronts which often merged together into much larger crack fronts forming the convex shaped ridges visible on the fracture surfaces following spalling. With continued sparking, the subsequent propagation and amalgamation of these cracks gradually undermined the surface (confirmed by the overhanging nature of the leading edge remaining after flake detachment) until eventually conditions prevailed whereby whole flakes of material were ripe for detachment.

Fig. 6. Spalled area on parent material revealed by removal of flake immediately prior to detachment.

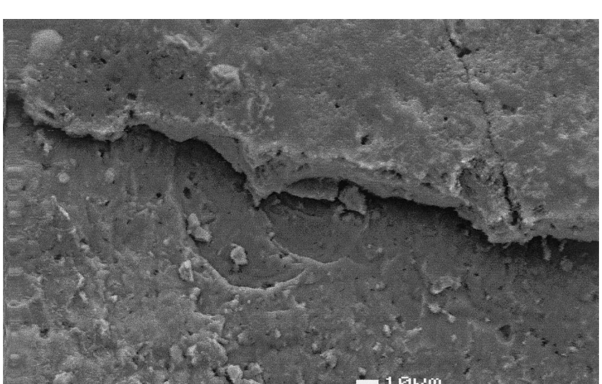

Fig. 7. Overhung appearance of leading edge as cracks penetrate into the material, undermining the surface and producing flakes characteristic of spalling.

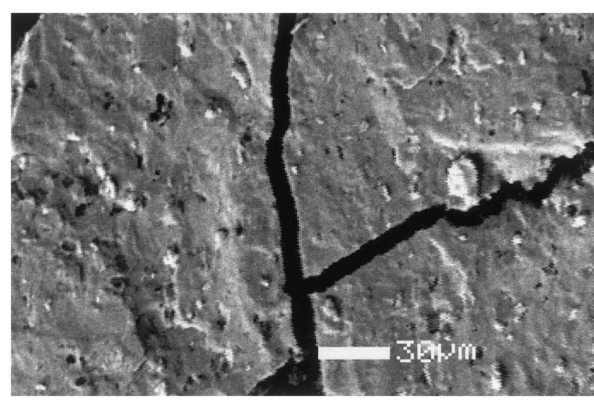

Fig. 8. Vacant holes and protruding particles of TiB_2 visible on underside of flake. Beach marks are also visible in the top left corner of the flake, indicative of crack progression.

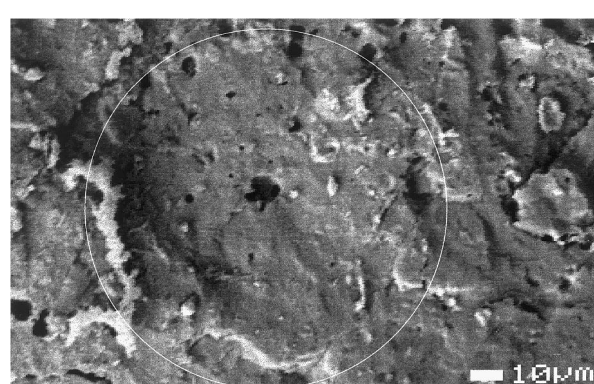

Fig. 9. Penny crack (highlighted) with central void where a TiB_2 particle once resided.

Vertically inclined cracks were identified which ran through the detached flake fragmenting it into smaller pieces. The exposed surface on the parent material from which the flake was detached did not reveal any visible signs of vertical cracking when examined by SEM, suggesting that any vertical cracks most likely initiated at some stage after the formation of horizontal cracking. The horizontal cracks therefore acted as a barrier or braking mechanism arresting the propagation of vertical cracks and limiting their extent of travel to the area above. Had the vertical cracks formed first, there would most likely have been some penetration beyond the horizontal cracking into the bulk material as it is unlikely that the vertical cracks would all form to the same depth. This was confirmed by subjecting the sialon-TiN composite to similar arcing conditions to induce spalling, and then sectioning the spalled area to examine the sub-surface damage.

The sialon–TiN composite was subjected to both normal sparking and abnormal arcing conditions to assess the extent of possible sub-surface damage for each machining regime.

During conventional or normal spark erosion of the sialon composite, there was no visible arcing during machining. SEM examination of the EDM machined surface revealed no evidence of surface cracking or large-scale spalling. When the spark eroded area was sectioned and polished, no evidence of sub-surface cracking was found. Under these ''normal'' machining conditions, the mechanisms by which material was removed were identified as being predominately dissociation, melting and evaporation, confirmed by the melt runs of recast material deposited on the surface. A micrograph of the polished section is shown in Fig. 11.

Examination of the spark eroded surface after machining under conditions which promoted sporadic arcing revealed sharp angular cracks within the recast layer. Sectioning and polishing revealed these cracks travelled within the material as near-vertical cracks, and the presence of horizontal cracking was also confirmed.

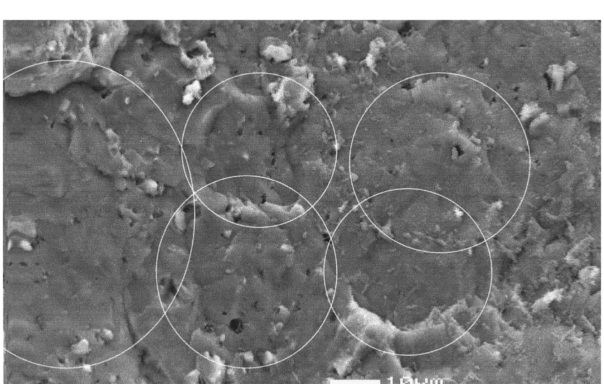

Fig. 10. Evidence of coalescing cracks (highlighted) on fracture surface.

Horizontal cracking invariably took the form of a principal crack often running parallel to the machined surface for up to several millimetres at near-constant depth, usually in the range from 50 to 300 μm below the surface, and accurately mirroring its profile. In all cases, near-horizontal cracks were periodically intersected by near-vertical cracks, the nature of which divided the overall crack formation into two categories.

The first category exhibited vertically inclined cracks which extended between the surface and horizontal crack, but not beyond it into the bulk of the material, as shown in Fig. 12. The horizontal crack can be seen running almost parallel to the surface at a depth of approximately 100–120 μm, but the vertically inclined cracks do not extend into the material beyond this depth. This sub-surface crack formation is in the early stages of creating, ready for detachment, a flake of over 1.0 mm across.

The second category of crack formation showed near-vertical cracks extending through and beyond any sub-surface horizontal cracking and into the bulk of the material, as shown in Fig. 13. Near-vertical cracks can be seen extending into the material to depths approaching

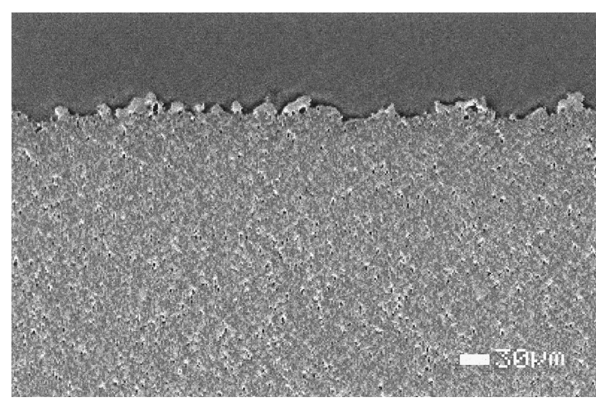

Fig. 11. Cross-section through EDM machined surface of sialon–TiN composite under normal machining conditions with no arcing (recast layer still attached).

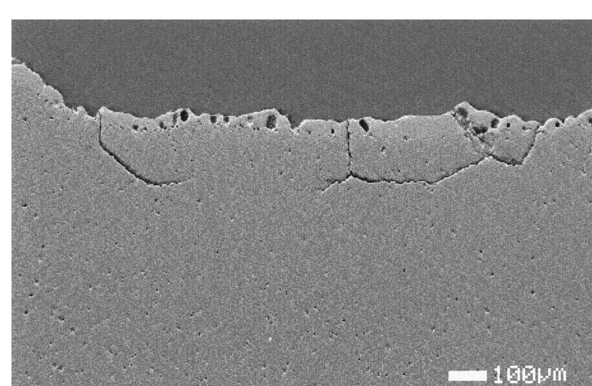

Fig. 12. Sub-surface near-horizontal cracks running almost parallel to the surface after machining under arcing conditions.

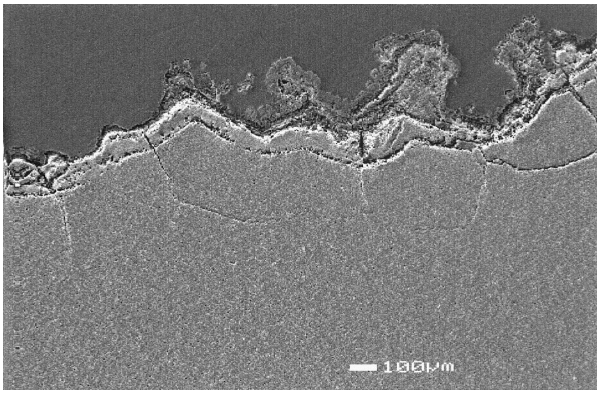

Fig. 13. Vertical cracking in sialon–TiN composite extending beyond the sub-surface horizontal crack into the bulk of the material (recast layer still attached).

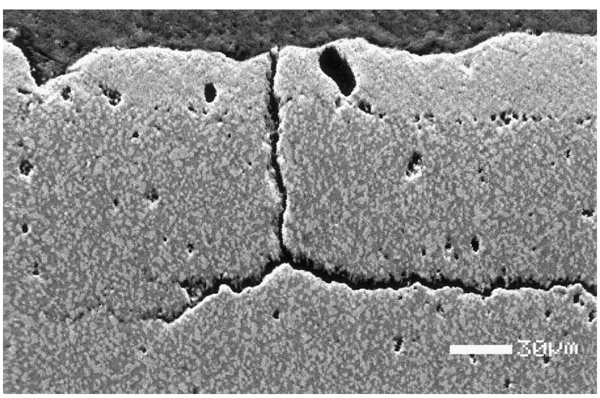

Fig. 14. Vertical crack running through recast layer showing no extension beyond sub-surface horizontal cracking. Note: recast layer contains high TiN entrapment and porosity.

600 μm. The principal sub-surface horizontal crack (or, more likely, a series of smaller coalesced horizontal cracks) appears to run almost parallel to the surface for approximately 2 mm at a near-constant depth of 100 μm.

The nature of the vertical cracking appeared to be different in each category. Where the depth of vertically inclined cracking was limited to the region above the horizontal crack, the polished sections showed either a direct singular intersection with the crack in the horizontal plane, as shown in Fig. 14, or they showed the vertical crack branching and then converging on the horizontal crack, eventually merging, as shown in Fig. 15.

In both materials, thermal mismatch between dispersoid and matrix is likely to have played a significant part in sub-surface crack initiation.

This thermal mismatch gave rise to an expansion ratio of 1.88:1 for the TiB_2 particles in the SiC composite, and 2.67:1 for the TiN particles in the sialon based composite.[9] As a result of the intense localised heating and cooling cycles imposed on the material during arcing and quenching, the greater expansion and contraction of the dispersoid particles which must occur under

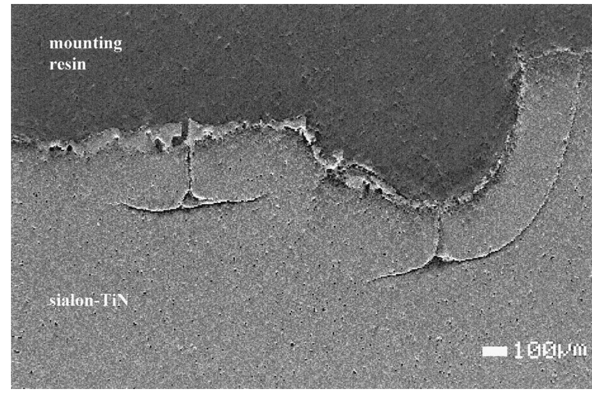

Fig. 15. Vertical cracks arrested at depth of horizontal cracks running parallel to the surface.

the constraints imposed by the surrounding matrix of each composition will give rise to fluctuating compressive and tensile stresses, this being particularly so for angular or irregularly shaped particles. Therefore, the dispersoid particles in these compositions are likely to act as nucleating points of crack initiation where the resultant stress concentrations exceed the tensile strength of the matrix material. This was confirmed by the existence of penny cracks, and was in agreement with Tvergaard's model.

The issue should be addressed as to why some near-vertical cracks extend below the depth of the main sub-surface horizontal crack whilst others do not, as this has significance in developing a practical spalling-based machining methodology. The answer to this question may lie in which cracks form first: the horizontal cracks or the vertical cracks, and also in the case of vertical cracking, whether the cracks are initiated on the surface or beneath the surface.

Where vertically inclined cracks extend deep below the sub-surface horizontal crack, it would seem likely that the vertical cracks may have formed before the horizontal crack, otherwise they would most likely have been halted as they ran into the underlying horizontal crack.

Deep vertical cracks extending from the material surface beyond the horizontal crack and into the material may have formed initially from a surface flaw, before the formation of sub-surface horizontal cracking, and then have been driven into the material as explained by conventional quenching theory. The sub-surface horizontal cracking may then have appeared afterwards, formed by the initiation, propagation and amalgamation of sub-surface penny cracks all forming at similar depths under the same tensile stress distribution, to give the appearance of vertical cracks running straight through the horizontal crack.

Once a sub-surface horizontal crack has been formed, there is a discontinuity within the matrix which will hinder further heat waves from flowing down below it, preventing the formation of further horizontal cracking at a greater depth until the material above the horizontal crack has flaked away. This explains why there is only one horizontal crack at any one time.

In the case of vertical cracks having their depth limited by the horizontal crack, as in Fig. 14, they are likely to have formed beneath the surface at some time after the horizontal crack was formed, not necessarily extending to the surface on formation, but only subsequently appearing to do so after further spark erosion had eroded the material surface away to expose them. Such an exposed crack might be expected to be covered by molten recast layer. Rather than sealing the crack, however, the recast layer with its high proportion of TiN (and therefore high contraction effect due to the higher thermal expansion coefficient) could part on freezing above the crack, allowing it to extend to the sample/dielectric interface.

During EDM machining, an additional factor in the spalling process is that dielectric will seep into any exposed cracks, and with each passing wave of heat, it will boil and expand with explosive force within the minute confines of the crack, propagating the crack through the material and eventually prising a spall or detached flake away from the parent material, leaving the adjacent undermined areas exposed for further erosion.

4. Conclusions

The feasibility of developing a novel and rapid machining regime for EDM of robust ceramic materials using arc-related discharges to generate thermal-shock induced spalling has been demonstrated to extend the EDM process beyond the boundaries of conventional sparking. If shallow sub-surface horizontal cracking is induced by electrical discharge and is the first cracking to form within the material, it has been shown to arrest any subsequently formed running vertical cracking and limit the extent of sub-surface damage to the region above. Where horizontal cracking is induced at a predictable depth through controlled thermal shock, this constitutes a very effective and reliable rough machining regime by fissile planing in which layers of material are removed by fracture mechanisms. Such a rough machining regime can be used prior to conducting a gentle finishing operation by conventional spark erosion to safely remove the final layer of any spall-damaged material by melting and evaporation.

Acknowledgements

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