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Modelling of fracture wear in vitrified cBN grinding wheels

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Analysis and modelling

ABSTRACT

Purpose: The paper describes modelling of fracture wear in vitrified cBN grinding wheels.
Design/methodology/approach: The approach used in the paper is based on using finite elements to model fracture wear processes in vitrified cBN grinding wheels. The approach used models fracture wear processes and ignores abrasive wear of the abrasive grains.
Findings: The findings show that during grinding the grain is subjected to forces that create fracture initiation zones in the sharp abrasive grains where tensile and compressive stresses dominate in certain parts of the abrasive grains.
Research limitations/implications: The findings show that further research is required that prevents the formation of crack initiation zones and considers the effects of wear flats on the magnitude of stresses in the abrasive grains.
Practical implications: The results imply that abrasive fracture wear is the dominant wear mechanism when grinding with sharp vitrified cBN grinding wheels.
Originality/value: The originality of this paper is reflected in the fact that this is the first time that fracture wear has been modelled in sharp vitrified cBN grinding wheels. The results presented in this paper will illuminate the need for accurate modelling of the wear of vitrified superabrasive grinding wheels.
Keywords: Artificial intelligence methods; Grinding; Tribology; Vitrified grinding wheels; Cubic boron nitride

1. Introduction

The grinding process relies on wear of the abrasive wheel, and the rate of wear plays an important role in determining the efficiency of the grinding process and the quality of the workpiece. The structure of a vitrified grinding wheel is composed of abrasive particles, a bonding phase, and distributed porosity to collect detritus and provide access for lubricants. The structure of a polished grinding revealing the nature of the grinding wheel is shown in Figure 1.

The wear behaviour observed is similar to that found in other wear processes; high initial wear followed by a steady-state wear regime. The third accelerating wear regime usually indicates rapid wear of the grinding wheel, which means that the wheel will need to be sharpened. This type of wear is usually accompanied by thermal damage of the machined workpiece.

The performance index used to characterize wheel wear resistance is the grinding ratio, or G-ratio, and is expressed as the experimentally determined ratio of the change in volume of the workpiece ground, Δv_w, to the change in the volume of the grinding wheel removed, Δv_s, and is shown in Eq. (1),

$$G = \Delta v_w / \Delta v_s \tag{1}$$

Grinding ratios cover a wide range of values ranging from less than one for vanadium-rich high speed steels [1] to over

60,000 when internally grinding M50 bearing races using cubic boron nitride abrasive wheels [2]. Previous attempts have been made on vitrified grinding wheels to address problems related to wear of abrasive grains in terms of brittle fracture [3,4]. The nature of different and interacting wear mechanisms involved, namely, plastic flow of abrasive, crumbling of the abrasive, and chemical wear, makes grinding wheel wear so complex that it cannot be explained using a single model.

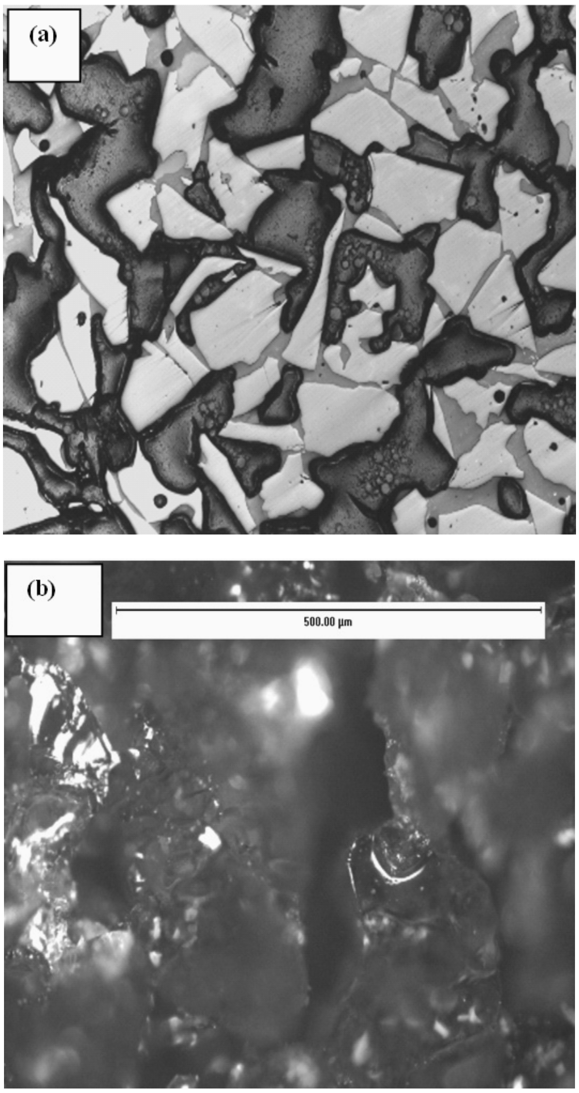

Fig. 1. Vitrified grinding wheel structure: (a) polished cross section showing relationship between grains, bonding phase and porosity; and (b) fractograph showing fractured grains ad glassy bonding phase

2. Wheel wear mechanisms

Three fracture wear mechanisms that contribute to the wear of grinding wheels (Figure 2) are identified as:

(a) Fracture of abrasive grains due to mechanical and thermal shock loads;
(b) Fracture of bond bridges; and
(c) Fracture at the interface between abrasive grain and bond-bridge.

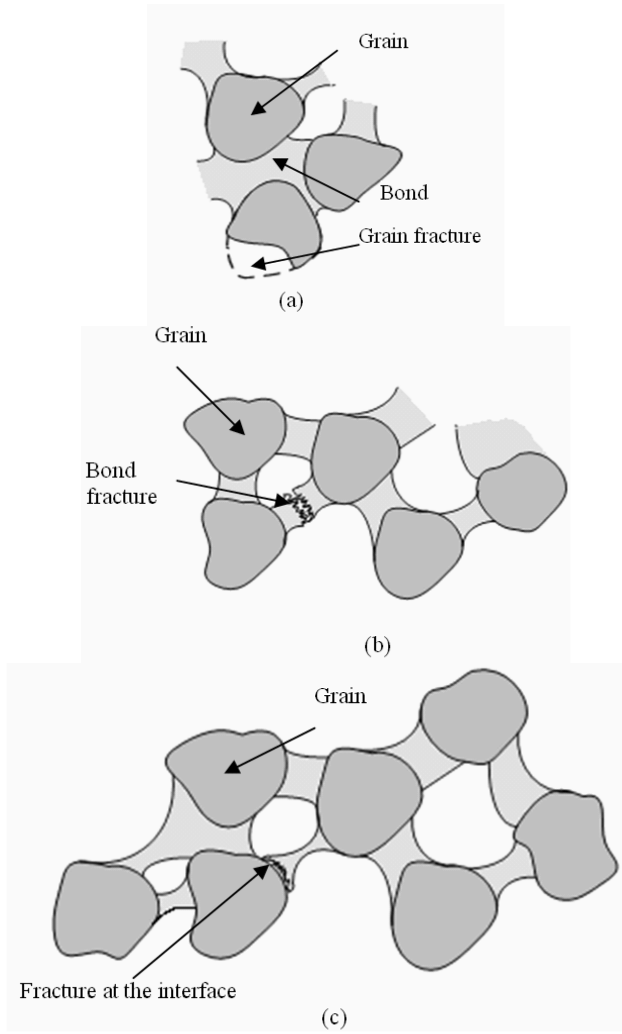

Fig. 2. Fracture wear. (a) Grain fracture, (b) bond fracture, (c) fracture between the grain and the bond

The occurrence of abrasive grain and bond fracture are considered simultaneously for the following reasons:

(a) They are of the same nature, i.e. fracture of brittle materials and hence brittle fracture is applicable to both bonding bridge and abrasive grain [3-5]. The applied thermal and mechanical loads cause initiation and further development of cracks that leads to fracture and the formation of irregular surfaces [6-10];
(b) They are related to dressing methods used and can occur simultaneously. The initial and final stages of wheel life between dressings exhibit fracture wear that is a combination of abrasive grain and bonding phase fracture;

(c) The relative amounts of bond bridge and abrasive grain wear cannot always be calculated. An investigation into precision grinding [3] that employed a soft wheel gave a high percentage of bond fracture, whereas a harder wheel gave partial abrasive grain fracture

However, the combination of grinding parameters such as equivalent chip thickness and the grindability of the workpiece material determines the dynamic wheel hardness, and so no single feature of the grinding process can be used to predict the fracture pattern of the wheel in advance. The difficulty when relating grinding wheel wear due to fracture to a particular grinding condition arises from the lack of knowledge about the loads applied to both abrasive grains and their bonding bridges and their response to those applied loads [11].

Tarasov [12] suggests that abrasive grain fracture occurs as a result of mechanical forces induced during chip formation, or thermal shock loads, induced by instantaneously high temperatures. Figure 3 shows chip formation during the initial stages of grinding. Hahn [11] proposed a thermal stress hypothesis to explain the fracture of abrasive grains. Plunge grinding experiments were conducted under fixed normal load conditions. Hahn asserted that as wear progresses measurements of torque indicated that the tangential force decreases. This led to the conclusion that abrasive grain fracture due to mechanical loading will not occur. Mechanical stresses were also considered as an explanation for the different rates of wear of the grinding wheels used during the experiments.

Bhattacharyya et al. [13] observed abrasive grain loss due to fracture using an electron microscope. They concluded that they could not differentiate between Peklenik's crystal splintering, i.e. grit flaking due to thermal stress, and abrasive grain fragmentation. However, they did explain their results in terms of Hahn's thermal shock hypothesis [11]. Hahn's experimental conditions suggested that attrition of the abrasive was expected to occur through abrasive wear. This suggestion was verified by Mohun [14] using abrasive discs. Wear measurements by Hahn [11] were based on the reduction in grinding wheel diameter, which Malkin and Cook [3] attributed to abrasive wear. Wear rates recorded were of the order of fifty microinches per second. It was expected that abrasive wear rates were in the region of five microinches per second. This rate was observed under less aggressive grinding conditions. Under aggressive grinding conditions, wear of the grinding wheel appeared to be more complex.

Malkin and Cook [3] collected wheel wear particles for each grade of grinding wheel when grinding using a fixed set of operating conditions. They analysed their size distributions statistically and discovered that a soft-grade grinding wheel (G-grade) produces 85% of grinding debris associated with bonding bridge fracture, whilst a harder-grade grinding wheel (K-grade) produces 55% of grinding debris associated with fractures of bonding bridges. Abrasive wear accounted for 4% of the total wear in both cases.

The strongest evidence in support of the idea of fracture due to mechanical loading is that fracture occurs some distance away from the cutting edge [4]. Yoshikawa [4] concluded that the heat generated by cutting has no effect on abrasive grain fracture since the peak temperature of the abrasive grain occurs at the surface of the grain in contact with the workpiece where fracture is initiated on cooling according to the thermal stress hypothesis. The hypothesis does not take account of any difference in the coefficient of thermal expansion between abrasive grain and bond bridges, and also the effect of thermal shocks on the quenching action of grinding fluids on the abrasive grain leaving the cutting zone.

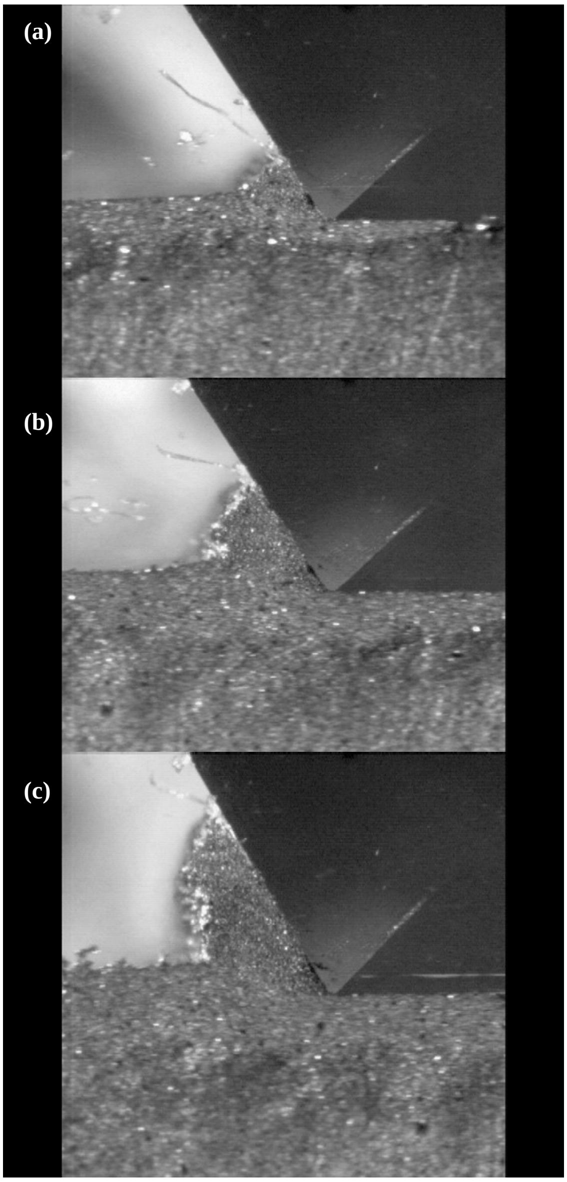

Fig. 3. Chip formation during the initial stages of grinding: (a) after 1s of grinding; (b) 2s; and (c) 3s

Saito and Kagiwada [15] analysed the latter case and reported that the thermal stress in an abrasive grain due to a pulsating heat source showed that the magnitude of the maximum tensile stress is not large enough to cause fracture of the grain. Eiss [16] and Malkin and Cook [3] adopted the mechanical loading approach. Eiss [16] applied a theoretical model of an idealised grain and compared it with experimental grinding data. Malkin and Cook

[3] derived an expression from first principles for the probability of bond fracture in terms of a bond stress factor. Yoshikawa [4] developed expressions for the probability of grain and bond fracture in terms of stresses in the abrasive grain.

Although bond and grain fracture are similar mechanisms, they have a different effect on the economics of the grinding process. The first mechanism results in a rapid loss of the grinding wheel, while the second mechanism, on a comparable scale with the un-cut chip thickness, generates sharp cutting edges and is known as the 'self-dressing action'. Both mechanical and thermal stresses appear to be responsible for fracture wear. The effect of heat at the abrasive grain and workpiece interface is responsible for locally affecting the mechanical properties of the abrasive grain.

However, fragments of larger sizes of abrasive grain are more likely to occur through mechanical loading that governs bond fracture and the self-sharpening action. A method of alleviating the onset of bond fracture due to unusually large mechanical loads is to dissolve deleterious particles in the bonding system that weakens the structure of the bonding bridge. In vitrified bonds, these particles are quartz particles that naturally occur in clay minerals. These particles reduce the load-bearing strength of the bonding bridges during vitrification heat treatment. Examples of grinding with cBN wheels are too numerous to mention and can be found in the literature.

3. Fracture wear model

Brittle materials exhibit high strength properties when loaded in compression. The ratio of rupture strengths is usually between 3:1 and 10:1 [17]. The existence of relatively low tensile stresses in the bond bridges, or the abrasive grains themselves, may cause failure by fracture to occur. To model the action of the grinding wheel [18], one must consider a single active cutting grain to be classed as a wedge of constant width loaded at its inverted apex with point loads, F, and, nF, which represent the tangential and radial force components with reference to the grinding wheel in which the grain is supported, and P is the resultant force (Figure 4). The stress distributions within point-loaded wedges can be determined using analytical methods [19], and the results of such an analysis indicate that if tensile stresses exist within the wedge then it will occur at its maximum along the rake face. The existence of a tensile stress depends on the magnitude of the force ratio, n. If the ratio is especially small that a tensile stress exists in the wedge, then for a specific force ratio the tensile stress is proportional to the tangential grinding force, F. Stresses of this nature would extend to, and beyond, the abrasive grain-bonding bridge interface. The fracture of abrasive grain, bonding bridge, or the interface between the two, depends on the particular grinding wheel used and the magnitude of the tensile stress induced during grinding.

Grains of cubic boron nitride (cBN) are up to ten times stronger in compression than in tension. The probability of grain fracture is likely to increase with an increase in tensile stress exerted in the grain, although the magnitude of the stress may be slightly higher than one-fifth the magnitude of the maximum compressive stress in the grain.

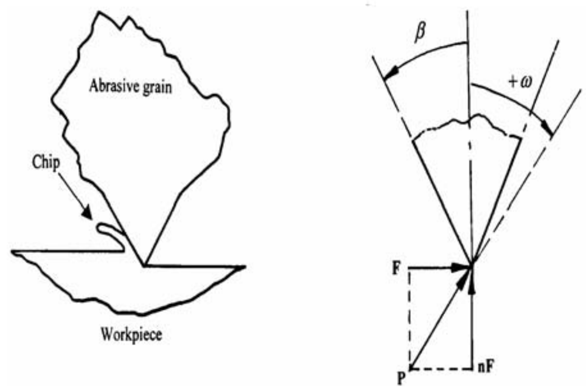

Fig. 4. Ideal wedge-shaped cutting point with no wear flat and the accompanying grinding force diagram

A significant barrier to the acceptance of stress patterns evaluated for such situations arises because point loads applied to perfectly sharp wedges produce infinitely high stresses at, and about, the point of contact. Therefore, the loads must be applied over a finite area. This implies that compressive stresses dominate over the finite area. Experimental results [20] show that rake face stresses are compressive over the entire length of chip-tool contact but are tensile outside of this region. The zone of fracture was located in the tensile zone at about two to two-and-a-half times the chip-tool contact length.

It seems likely that higher tensile stresses are associated with higher grain fractures resulting in rapid loss of grinding wheel grains and, consequently, lower grinding ratios. The wear model should incorporate the fact that the loads are spread over a finite area of the grain. This implies that point loads can be resolved along the rake face, or can be, applied directly along the rake face of the cutting tool. The model should allow the examination between the wear rate of a grinding wheel and the stresses established in active cutting grains subjected to grinding forces. Therefore, grinding force data and grinding ratios from the vitrified cBN grinding experiments have been used to validate the wear model. This means that it is necessary to estimate the force components of grinding on each active cutting grain.

The number of active cutting grains is estimated by driving a grinding wheel into a piece of lead that has a length equal to the grinding wheel's circumferential length. The depth to which the grinding wheel is driven into the length of lead is equal to the depth of cut. The impression that the grinding wheel produces in the length of lead is equal to the number of cutting points that are active during the grinding stroke at that particular depth of cut. However, the grinding wheel must be prepared by simulating the grinding conditions used during the experimental test conditions. Once the grinding wheel has stabilized at its optimum cutting condition, then the wheel is removed from the grinding machine and driven into the length of lead.

The force components are then applied to a 'model' abrasive grain by dividing the grinding force data into the number of active cutting grains over an area that simulates the abrasive grain-workpiece contact area. Stresses established in this area are calculated using finite elements. The wear of the grinding wheel, expressed in terms of a grinding ratio, and its relationship to the stress levels set up in the model grain is investigated by correlation and regression techniques.

4. Analysis of stresses

The geometry of an ideal grain in the vicinity of its cutting edge is a simple symmetrical wedge of constant width with an included angle of 70˚ that results in a rake angle of –35˚. There is no wear flat on the model cutting grain. In order that a finite element method is used to evaluate stresses in the wedge, the wedge was subdivided into 210 diamond-shaped elements with a total of 251 nodes. Forty-one nodes were constrained at the boundary of the wedge and the leading five nodes on the rake face were loaded (Figure 5). The tangential and normal grinding forces were replaced by equivalent forces (F_Y and F_Z) acting perpendicular to (normal load) and along (shear load) the rake face of the wedge. The concentrated loads at the five nodes are representative of the distributed and normal loads acting on the rake face over the abrasive grain-chip contact length.

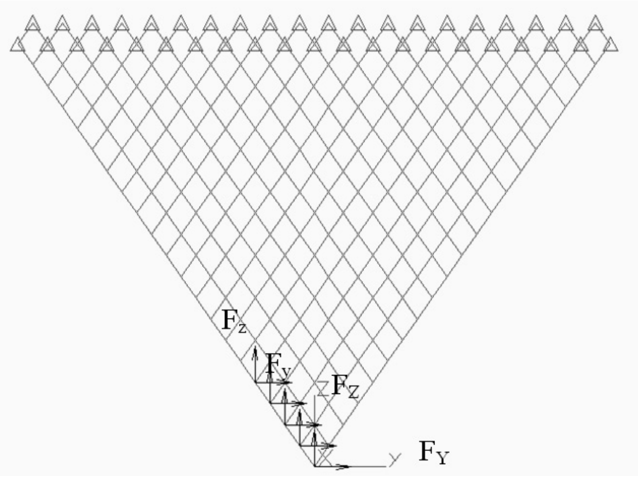

Fig. 5. Finite element assemblage with grinding loads applied at the rake face nodes

The normal force distribution on the rake face was taken to be maximum at the cutting edge and decreasing linearly to zero at the end of the abrasive grain-chip contact length. The shear force was taken to be constant over the first half of the contact length, decreasing linearly to zero over contact length. Grinding loads were also applied directly to the rake face and at the tip of the grain without calculating equivalent forces. This was performed in order to compare and contrast the effect of different force distributions on the stresses generated within the abrasive wedge.
A further model was developed to discover whether bonding bridges, and their shape, affected the stress distributions observed in the model grains, and to discover if there was a transition from grain fracture to bond fracture when grinding with a perfectly sharp abrasive grain. The same methodology of applying loads to an idealised wedge was applied to the abrasive grain-bond bridge models. Figure 6 shows the general arrangement of the finite element assemblage of a diamond-shaped abrasive grain with two bond bridges attached to its primary faces. The ends of the bond bridges are constrained from moving. The models were evaluated for stress distribution within grain and bonding bridge and corresponding displacements were noted. To discover whether there was a simple relationship between maximum tensile stress and the wear rate of the grinding wheel, a correlation between maximum tensile stress and grinding ratio was established. In all cases, an acceptable correlation was obtained. Further analyses involved the reduction in the thickness and shape of the bonding bridges. Figure 7 shows a typical finite element construction of such a model. To measure the value of using the maximum tensile stress as a way to estimate grain fracture tendency, the correlation between the two sets of data were calculated.

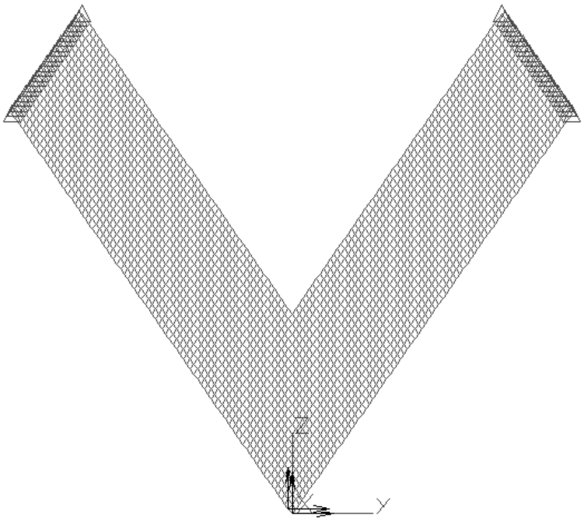

Fig. 6. Finite element assemblage of cBN abrasive grain with vitrified bond bridges attached to the grain showing attached grinding loads

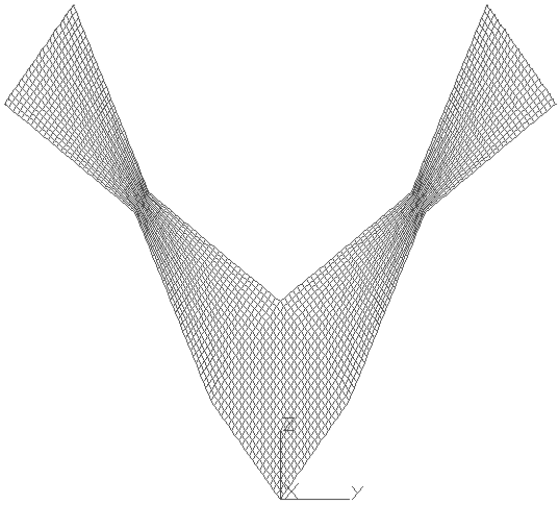

Fig. 7. Finite element model of cBN abrasive grains attached to bond bridges that are representative of real, vitrified bond bridges. Grinding loads are attached to the tip of the grain

The region of fracture initiation was also located using Griffith's criterion of fracture. For,

$$\frac{\sigma_c}{\sigma_t}\sigma_1 + \sigma_3 > 0 \tag{2}$$

Then, $\sigma_1 = \sigma_t$ (3)

but for, $\frac{\sigma_c}{\sigma_t}\sigma_1 + \sigma_3 < 0$ (4)

then,

$$\left(|\sigma_1| - |\sigma_3|\right)^2 + 8\sigma_t\left(|\sigma_1| - |\sigma_3|\right) = 0 \tag{5}$$

Where σ_1 and σ_3 are the principal stresses, assuming that $\sigma_1 > \sigma_3$, σ_t is the ultimate tensile stress of the abrasive or bonding bridge material, and σ_c is the ultimate compressive stress. For cBN grain material, the ratio of σ_t and σ_c is ~ 0.1, and for the alumino-borosilicate bonding material it is ~ 0.25.

5. Experimental results and discussion

The results of the two-dimensional stress analyses were consistent with the experimentally determined stress distribution obtained by Loladze [20] when cutting soft metal with photoelastic tools. The maximum tensile stress always occurs at the rake face at a distance from the cutting edge ranging from 1.5 – 4 times the abrasive grain-chip contact length, the exact magnitude of the coefficient depends on the loading conditions for a particular machining event. For a given value of the tangential force component, F, a higher force ratio, F/nF, generates a maximum tensile stress that migrates along the rake face further away from the cutting edge. These results indicate that mechanically induced fracture occurs at a finite distance away from the cutting edge. When using Griffith's criterion, the influence of mechanically induced stresses indicate that fracture initiation zones are established. Figure 8 shows the occurrence of such zones in an idealised wedge. The first zone is located around the point of maximum tensile stress and is always at the rake face. (Fig.9.)

Failure in this zone is tensile in nature and would initiate fracture at a point on the rake face of the order of two-to-three times the abrasive grain-chip contact length away from the cutting edge. This type of fracture is consistent with fracture on a scale comparable with the chip thickness and tends to produce the so-called 'self-dressing action'. The second much smaller zone is located at the immediate vicinity of the cutting edge. Failure is compressive in this region and results in small scale crumbling of the cutting edge leading to the formation of a wear flat on the abrasive grain.

The correlation between the magnitude of the maximum tensile stress in the model abrasive grains and the appropriate grinding ratio (Table 1) is high and is dependent on the way the forces are applied to the grains and less so on the type of bonding bridge used that supports the abrasive grains. It would be expected that the higher the tensile stress, the greater is the rate of grinding wheel wear and consequently the corresponding grinding ratio. Perfect linear correlation in accordance with this would result in a correlation coefficient of –1.

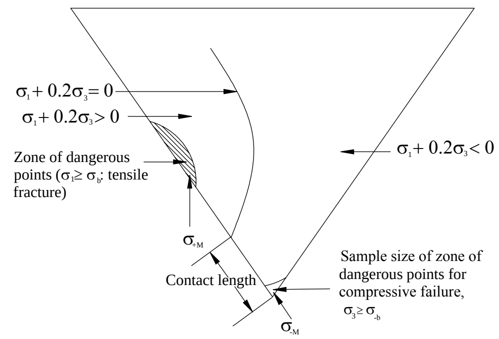

Fig. 8. Griffith's criterion applied to the idealized wedge showing tensile and compressive fracture initiation zones

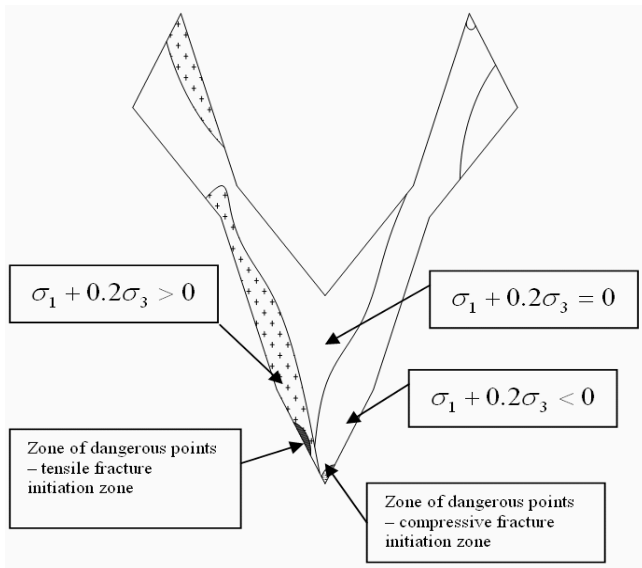

Fig. 9. Griffith's criterion applied to the cBN abrasive grain with adjacent bonding bridges

Table 1.
Correlation coefficient between maximum tensile stress and grinding ratio for a variety of finite element model abrasive grain-bond bridge models. Comparison is also made between the methods of applying loads to the abrasive grain models

Abrasive-bond model	Equivalent forces	Directly-applied forces
Idealized wedge	-0.859	-0.997
Unit thickness bond-bridge	-0.828	-0.998
0.5 thickness bond-bridge	-0.832	-0.997
0.33 thickness bond-bridge	-0.832	-0.997
0.25 thickness bond-bridge	-0.838	-0.998
0.2 thickness bond-bridge	-0.849	-0.998

The correlation coefficient between the maximum tensile stress and the grinding ratio is significant. This is to be expected as the force ratio may vary slightly. However, if the tangential component of the grinding force changes significantly without a change in force ratio, then it is expected that the maximum tensile stress will change significantly and reduce the grinding ratio.

Table 1 shows that for perfectly sharp vitrified cBN grinding wheels the correlation coefficient is insensitive to changes in the geometry of bonding bridges that are attached to the abrasive grains. This is logical when one considers that the tensile fracture zone always occurs in the abrasive grain and not in the bonding bridge (Figure 7).

The calculation and application of equivalent grinding loads produces a lower correlation coefficient compared to directly applied grinding loads. This implies that grinding loads are simply not point loads acting at the tip of the inverted apex and along the abrasive grain-chip contact length of the grinding grain. In fact, directly applied grinding forces produce better correlation coefficients. This means that for perfectly sharp vitrified cBN grinding wheels, one must apply the component grinding loads directly to the rake face.

It can be seen from Table 1 that induced tensile stresses account for the loss of grain material from a grinding wheel. Therefore, the maximum tensile stress is the best indicator of grinding wheel performance, in terms of grinding ratio, during a grinding operation.

6. Conclusions

For perfectly sharp vitrified cBN grinding wheels, grain fracture appears to be the dominant cause of abrasive material loss during a grinding operation.

Grain fracture is much more likely to be caused by mechanically induced tensile stresses within abrasive grains than by mechanically induced compressive stresses.

The best indicator of wheel performance during a grinding operation under different operating conditions is the level of tensile stress established in abrasive grains. High tensile stress levels in abrasive grains are associated with grain fracture and relatively high grinding ratios in perfectly sharp grinding wheels.

Finite element models of perfectly sharp cBN grinding grains can be applied to grinding wheels where the dominant wear mechanism is grain fracture.

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