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Machining Performance of Phase Transformation Toughened Alumina and Partially Stabilised Zirconia Composite Cutting Tools

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Abstract

Phase transformation toughened zirconia (TTZ) doped with yttria or ceria has excellent properties such as higher order fracture toughness, thermal shock resistance and moderate hardness. With these qualities, they are able to exhibit machining performance comparable to cold-compacted Al_2O_3 cutting tools. With an addition of 20% aluminium oxide to TTZ, i.e. the composites of alumina and partially stabilised zirconia (PSZ) exhibit improved toughness, enhanced thermal shock resistance and hardness. The alumina and PSZ composite ceramic tools exhibit cutting performance better than TTZ tools and comparable to zirconia toughened alumina tools.

Durch Phasentransformation (TTZ) verstärktes und mit Yttriumoxid oder Zeriumoxid dotiertes Zirkoniumoxid hat ausgezeichnete Eigenschaften, wie z.B. hohe Bruchzähigkeit, Thermoschockresistenz und mäßige Härte. Mit diesen Eigenschaften läßt sich der Werkstoff in seiner Qualität als Schneidewerkzeug mit kaltgepreßtem Al_2O_3 vergleichen. Mit einem Zusatz von 20% Aluminiumoxid zu TTZ, d.h. ein Verbund aus Aluminiumoxid und teilstabilisiertem Zirkoniumoxid (PSZ), zeigt der Werkstoff verbesserte Zähigkeit, verstärkte thermische Schockresistenz und Härte. Die PSZ Verbundkeramikwerkzeuge haben eine bessere Schneideleistung als TTZ-Werkzeuge und sind vergleichbar mit Werkzeugen aus Zirkoniumoxid-verstärktem Aluminiumoxid Werkzeugen.

Les zircones renforcées par transformation de phase (TTZ), dopées à l'oxyde d'yttrium ou de cérium ont d'excellentes propriétés, telles qu'une ténacité à la rupture très élevée, une résistance aux chocs thermiques et une dureté moyenne. Avec de telles qualités, elles peuvent présenter des performances d'usinage comparables aux outils de coupe en Al_2O_3 pressée à froid. Par l'addition de 20% d'alumine à la TTZ, les composites d'alumine et de zircone partiellement stabilisée (PSZ) présentent une ténacité améliorée de même que leur résistance aux chocs thermiques et que leur dureté. Les outils en céramique composite alumine-PSZ présentent des performances de coupe meilleures que les outils en TTZ et comparable à celles des alumine renforcée par la zircone.

1 Introduction

Advances in ceramic processing technology have resulted in a new generation of high-performance ceramic cutting tools exhibiting improved properties through microstructural engineering. Control of microstructure has been the route by which major improvements have been made in tool properties such as fracture strength, toughness, thermal shock resistance, creep resistance, hardness and wear resistance. The advances have resulted in the emergence of newer materials in both oxide and non-oxide group. Control of microstructure such as particulate reinforcement by which traditional Al_2O_3 has been reinforced by the addition of TiC (30%) has resulted in the development of traditional commercial-grade black ceramics. Such tools have been reported to perform[1,2] better than traditional cold-compacted Al_2O_3 tools. However, manufacturing constraints have limited their applications.

Apart from the black ceramics, among the oxide group emergence of transformation toughened ZrO_2 known as ceramic steel has widened the scope of application of oxide ceramics such as higher cutting speed limits, interrupted cutting and the like. Zirconia exists in three well-defined polymorphs: cubic (*c*) (above 2370°C), tetragonal (*t*) (between 2370 and 1150°C) and monoclinic (*m*) (below 1150°C).[3] The high temperature phases can be stabilised to room temperature by the addition of dopants like yttria, ceria, or magnesia. Transformation toughened zirconia (TTZ) with yttria content 2–3 mol% or ceria up to 20 mol% consists of single *t* phase structure at room temperature. The *t* phase which is a metastable phase at low temperatures needs energy to transform to the more stable low-temperature *m* phase.[4]

Since this *t* to *m* transformation absorbs energy, and since the ability of a material to absorb energy is its toughness,[5] this *t* to *m* transformation leads to an increase in the toughness of the material. Hence, the material is said to be toughened and this phenomenon is termed transformation toughening.[6]

Usually two types of stabilisation occurs in TTZ. They are the thermodynamic and kinetic stabilisations. This is schematically illustrated in Fig. 1.[7] Each phase has a given free energy at a given temperature and the difference in free energy ΔG determines the stability of each phase. The phase changes can occur at the equilibrium temperature, when $\Delta G = 0$. This is the thermodynamic stabilisation. The metastable phase can be retained at lower temperatures, if sufficient energy has not been provided, i.e. the metastable phase is kinetically stabilised, while the forward phase transformation $m \rightarrow t$ is thermodynamic in nature, the reverse $t \rightarrow m$ transformation is kinetic or stress induced. Thus, during service, the TTZ experiences both thermodynamic and kinetic stabilisation.

Introduction of adequate quantity of TTZ in traditional alumina matrix has led to the development of zirconia toughened alumina (ZTA) with improved toughness. In ZTA the ZrO_2 experiences a constrained transformation, the constraining matrix is Al_2O_3 which has a higher elastic modulus and lower thermal expansion than TTZ. The application range of TTZ, ZTA and other engineering ceramics are presented in Fig. 2.[8] It is seen that ZTA is suitable for relatively lower order temperatures and higher order stress. Studies on ZTA by Narutaki *et al.*[9] have reported that while ZTA exhibited superior resistance to crater wear in face milling, there was no improvement in crater resistance in plain turning. The superiority of the tool performance in milling can be attributed to possible cyclic $t \rightarrow m \rightarrow t$ transformation of ZrO_2 during milling, maintaining the harder *t* phase on the rake face, thereby facilitating enhanced resistance to crater. Investigations on the dynamic fatigue and wear resistance of ZTA has revealed that stress-induced (kinetic) transformation resulted in a decrease in sub-critical crack extension velocity, enhancing thereby the static fatigue performance. However, the wear resistance of ZTA was reduced when compared with that of pure alumina. This was attributed to the occurrence of microcracks on the surface due to stress-induced transformation.[10] It has been found that the composites of yttria–PSZ (80%) and alumina (20%), fabricated by hot isostatic pressing (HIPing) using sub-micrometre powder as starting material exhibited higher order fracture toughness and fracture rupture strength. The improved mechanical properties of composites of alumina and PSZ material can be used to the advantage for many engineering applications including metal cutting. This paper illustrates the

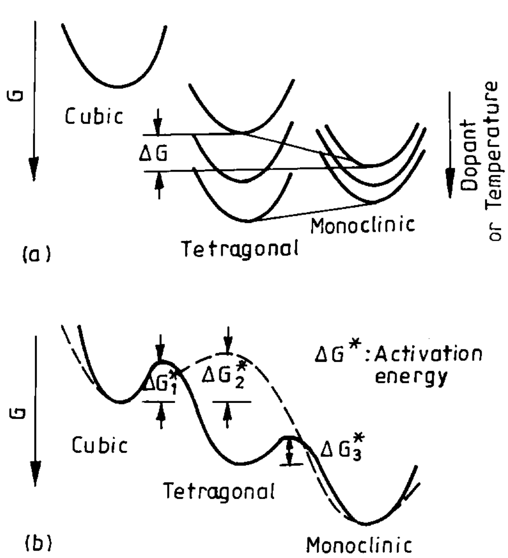

Fig. 1. Types of stabilisation: (a) thermodynamic, and (b) kinetic.

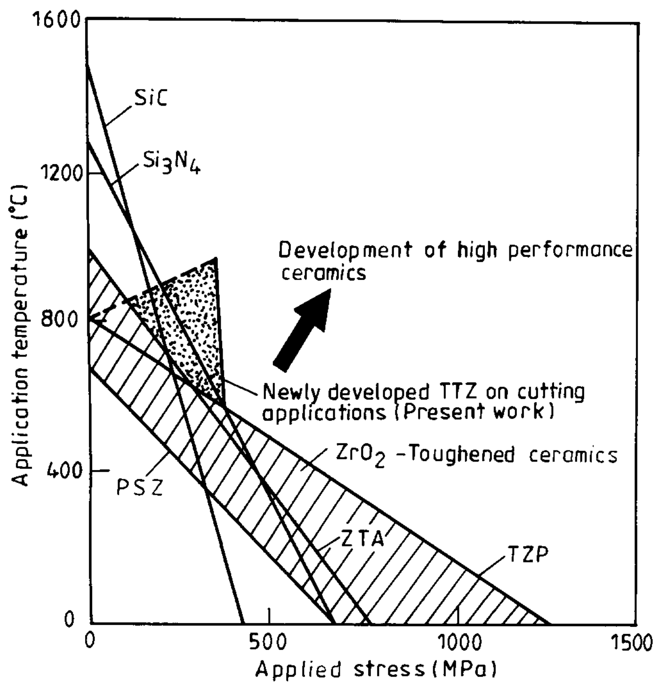

Fig. 2. The potential application range of engineering ceramics.

Table 1. Properties of composites of alumina and PSZ[a]

Property	*Notation*	*As sintered*	*Sintered and HIPed*	*Units*
Young's modulus	E	250	260	GPa
Poisson's ratio	ν	0·3	0·3	
Thermal conductivity	K	5·435 5	5·648 6	W/m C
Thermal expansion coefficient	α	9·6	9·4	$\times 10^{-6}$/°C
Thermal diffusivity	D	2·0	2·0	$\times 10^{-6}\,m^2/s$
Fracture toughness	K_{Ic}	5·28	8·28	$MPa\,m^{1/2}$
Bending strength	σ	426	593	MPa
Hardness	H	1 350	1 500	H_v
Density	ρ	5·10	5·30	g/cm^3
Phase at surface		α-$Al_2O_3 + t + c$	α-$Al_2O_3 + t + c$	
Fracture surface energy	γ_i	5·073 8	11·997 7	$\times 10^{-5}$ MPam

[a] Processing schedule: 200 MPa green-pressed compact; sintering 1500°C/2 h; HIPing 1450°C/1 h, 190 MPa.

Table 2. Thermal shock parameters of composites of alumina and PSZ

Thermal shock parameter	*Expression*	*As sintered*	*Sintered and HIPed*	*Units*
R	$\sigma(1-\nu)/E\alpha$	124·25	169·84	°C
R'	RK	675·36	959·36	W/m
R''	RD	248·50	339·68	$\times 10^{-6}\,m^2$ °C/s
R'''	$E/\sigma^2(1-\nu)$	1·968 0	1·056 25	$(MPa)^{-1}$
R''''	$R'''\gamma_i$	99·852	126·725	$\times 10^{-6}$ (m)
ΔT_c	—	200	200	°C

application of composites of alumina and PSZ material as a cutting tool for machining spheroidal graphite iron and C60 steel.

1.1 Mechanical and thermal properties of starting material

For good performance, a cutting tool material should possess high fracture toughness, thermal shock resistance and bending strength apart from high hot hardness. The properties of composites of alumina and PSZ evaluated are presented in Table 1. The thermal shock parameters evaluated are presented in Table 2.

2 Experimental Procedure

Turning trials have been conducted on SG iron and C60 steel in a high-speed precision VDF lathe using three types of ZrO_2 inserts prepared at the laboratory and a commercially available ZTA insert. The inserts were ground using an optical profile grinding machine; the inserts were provided with negative T-land of 200 μm over the cutting edges. The machining conditions and other details are presented in Table 3. The performance of the cutting tools were evaluated by measurement of flank wear and surface finish of turned workpieces.

3 Results and Discussions

3.1 Surface texture influenced by transformation toughening

Control of surface texture in turning is largely influenced by the machining feed and form stability of the cutting nose. An ideal turning tool is one which has a fidelity of replication of its nose on the surface, thereby ensuring good control over surface texture. Traditional Al_2O_3 cutting tools exhibited inconsistent performance owing to sudden chipping/spalling[2] over the cutting nose due to thermal cracking, chemical reaction with the ferrous work material forming Fe_xO_y–Al_2O_3 spinels and cumulative fatigue damage. However, TTZ material doped with yttria or ceria have exhibited enhanced resistance to mechanical and thermal shocks due to the phenomenon of transformation toughening. While the stress induced over the cutting zone can produce a reverse $t \rightarrow m$ phase transformation (kinetic stabilisation), the heating can retransform $m \rightarrow t$ phase. While the $t \rightarrow m$ transformation is associated with volume expansion and consequent toughening of the tool material, the forward transformation $m \rightarrow t$ results in higher hardness. Thus, a TTZ material exhibits toughening without chipping which can maintain better surface texture in turning.

Table 3. Machining conditions

• Machine	VDF lathe
• Spindle power	18 kW
• Cutting velocity used	200–600 m/min
• Feed rate	0·063 mm/rev
• Depth of cut	0·75 mm
• Cutting tool materials	

(1) Composites of alumina and PSZ: 20% wt Al_2O_3 and 80% wt ZrO_2 (3 mol% Y_2O_3–ZrO_2): sintered.
(2) Composites of alumina and PSZ: 20% wt Al_2O_3 and 80% wt ZrO_2 (3 mol% Y_2O_3–ZrO_2): sintered and HIPed.
(3) Mixed composition: 50% wt ZrO_2 (2 mol% Y_2O_3–ZrO_2) and 50% wt ZrO_2 (12 mol% CeO_2–ZrO_2).
(4) ZTA: 4·2% wt ZrO_2 + 0·3% wt MgO + 95·5% wt Al_2O_3.

• Tool geometry

γ	α	λ	κ	θ	r
−6	5	−5	75	90	1·6

where γ is the side (main) rake angle (°); α is the side (main) relief angle (°); λ is the angle of inclination of the side (main) cutting edge (°); κ is the plan approach angle (°); θ is the included angle between the cutting edges (°); and r is the nose radius (mm).

Figure 3 illustrates a typical variation of surface finish with the time of machining for different tools. It is seen that while the tools experiencing toughening under constraint maintain a good control over the texture, the plain mixed composition exhibited a wider variation. Referring to Fig. 3, it is seen that for all the tools, the surface roughness exhibited a rising trend, up to a certain time of machining beyond which there was an improvement in surface finish. The improvement can be attributed to the deformation of nose-associated transformation toughening of the respective tool materials.

For understanding the status of the tool material over the nose portion, X-ray diffraction (XRD) patterns of each tool material before and after a certain amount of machining time were recorded. Figure 4 is the XRD pattern of each tool material used in the present study. It is seen that all the tools exhibited a certain amount of *m* phase after machining, indicating phase transformation and associated toughening. According to classical theory of constrained phase transformation as in the case of a ZrO_2–Al_2O_3 system, the strain energy for phase transformation depends on the elastic properties of the constraining matrix and the residual strain that pre-exist in the untransformed state. For ZrO_2, the ideal constraining matrix is the Al_2O_3 owing to its higher elastic modulus and lower thermal expansion coefficient. The shift in the occurrence of maximum roughness (points A and D) for different tools in Fig. 3, can be attributed to the reduced transformation energy (and consequent early phase transformation)

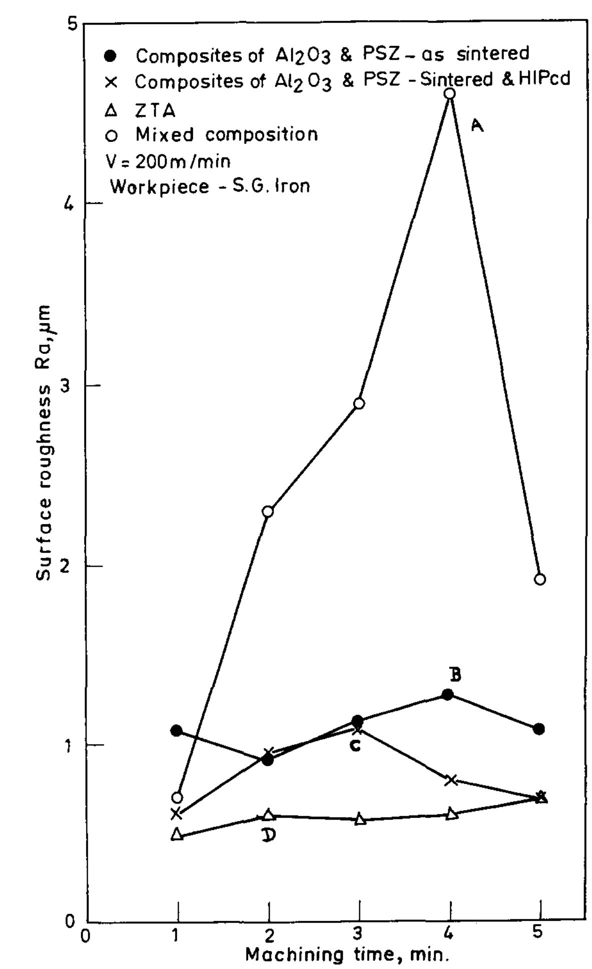

Fig. 3. Variation of surface roughness with machining time.

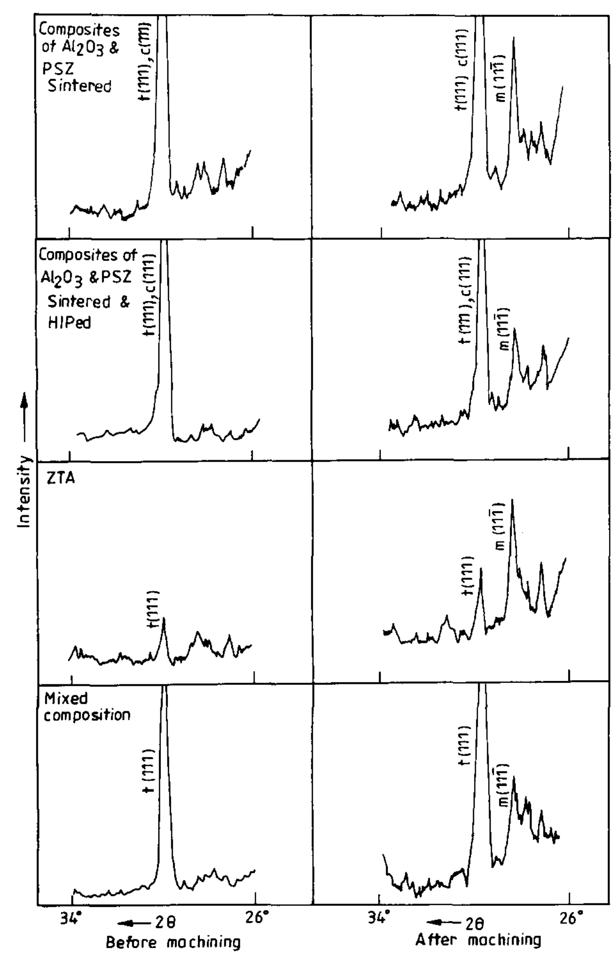

Fig. 4. XRD patterns showing phase transformations during machining SG iron at $V = 200$ m/min of CuKα radiation.

due to matrix constraint. The difference in the shift between points B and C is attributed due to additional residual strain due to HIPing.

3.2 Influence of cutting speed and work material in surface roughness

The role of transformation toughening on surface texture control, can be seen in the influence of cutting speed on surface roughness. The variation of surface roughness observed with cutting speed is presented in Fig. 5. It is seen that for both the tools, the surface roughness registered a dip with increasing velocity. With increasing cutting velocity the cutting temperature will usually increase thereby resulting in higher order quenching stress; this results in $t \rightarrow m$ transformation, producing more toughening and deformation around the cutting nose (in the cutting plane), resulting in observed reduction in surface roughness. From the observation on surface roughness, it can be seen that there exists a critical velocity, V_c, for each tool material around which there is only a marginal variation in surface roughness. For composites of alumina and partially stabilized zirconia, the V_c was around 400 m/min, and for ZTA it was around 300 m/min. The difference in the V_c can also be attributed to the role of constraint on transformation toughening of composites of alumina and PSZ. The higher order roughness in the case of composites of alumina and PSZ tool, can be attributed to the deficiencies in the mechanical properties of composites of alumina and PSZ tool compared to that of ZTA; the occurrence of c phase in the matrix (Table 1) and the absence of CIPing in the compaction schedule have reduced the bending strength and FRS values and thereby the performance.

Figure 6 presents the variation in R_t values with cutting speed. The drop in R_t values for cutting velocities greater than V_c, indicates that under such conditions, the machined surface texture could have been partially burnished due to deformation of the toughened cutting nose.

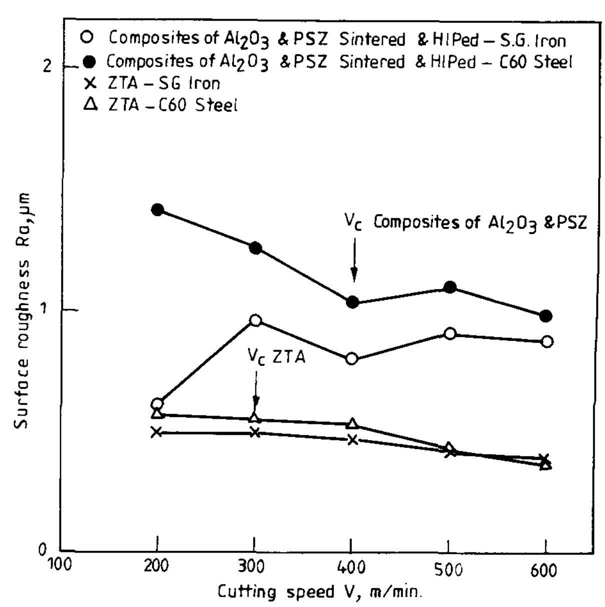

Fig. 5. Performance of composites of alumina and PSZ in surface production.

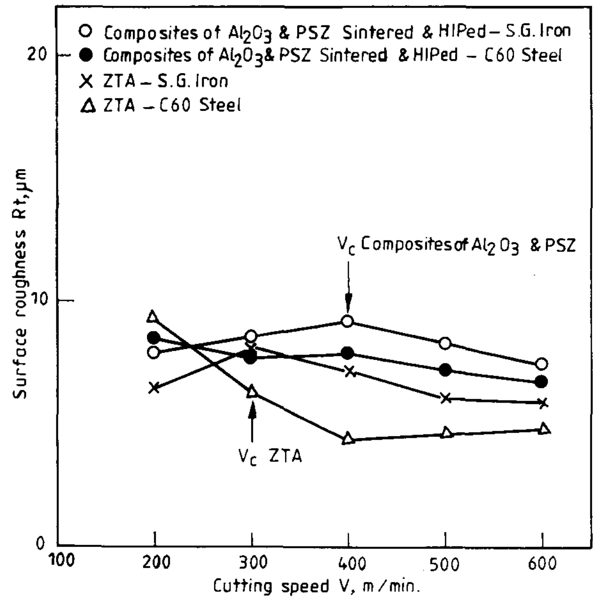

Fig. 6. Variation of R_t with cutting speed.

3.3 Flank wear observation

While form stability of the cutting wedge controls the machined surface texture, the flank wear influences the control of diameter in turned workpieces. For evaluating the performance of ceramic cutting tool for control of tolerances, the flank wear of composites of alumina and PSZ was measured. Figure 7 presents the variation of flank wear, VB, as influenced by machining time and cutting speed. It is seen that depending upon the work material, there is a definite cutting velocity around which the trend of

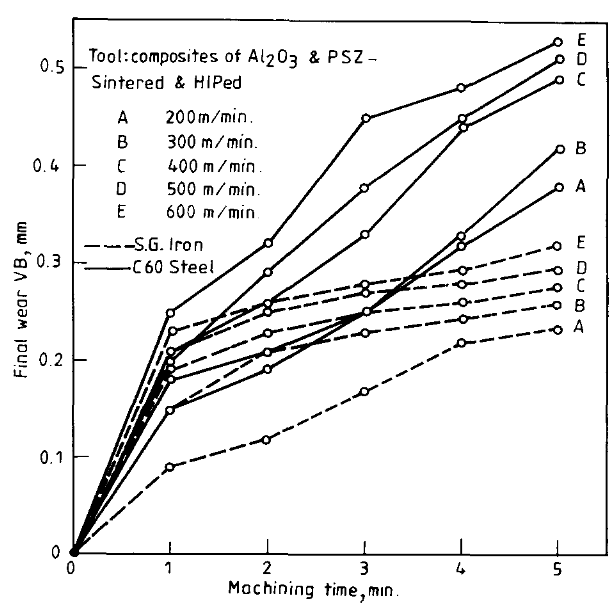

Fig. 7. Flank wear of composites of alumina and PSZ sintered and HIPed tool influenced by work material.

wear propagation changes. It is around 200 m/min for SG iron, while it is 200–300 m/min for a C60 steel workpiece. Flank wear of the cutting tool is usually associated with abrasion of the tool flank, localised small-scale discrete plastic deformation of the asperities in the flank surface, or/and combination of these two. The increase of flank wear of composites of alumina and a PSZ tool for a cutting velocity greater than 200 m/min, for SG iron can be mostly attributed to abrasion of the tool flank.

While machining C60 steel, the composites of alumina and PSZ tool experienced wider but smoother flank wear. An intense sliding of just machined C60 steel surface over the tool flank, usually promotes localised deformation of the asperities over the tool flank resulting in a smoother and wider flank land due to small-scale discrete plastic deformation.

4 Conclusions

The first ever machining trials carried out on composites of alumina and PSZ revealed that

- composites of alumina and PSZ can be utilised as a cutting tool material to advantage;
- the performance of composites of alumina and PSZ tool was comparable to that of commercial ZTA tools; and
- the performance of composites of alumina and PSZ tools can be further improved by eliminating the *c* phase, by adopting a better sintering schedule.

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