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Cutting Tool Application of Ceria-Zirconia

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Abstract

Transformations between the tetragonal and monoclinic phases of stabilized zirconia, popularly known as transformation toughening, have been widely studied. The transformation response of these phases to temperature and stress are quite different and hence their transformation response to an environment such as metal cutting, where both temperature and stress effects are involved simultaneously, is of interest. Since any processing may lead to transformations and phase changes, there has been no report on the application of these transformation toughening materials. The present paper deals with the techniques of fabricating a ceramic cutting tool based on ceria stabilized zirconia without phase destruction. The machining performance of this tool in machining cast iron is evaluated and its transformation behaviour in the metal cutting environment is studied.

Die Transformation zwischen der tertagonalen und der monoklinen Phase von stabilisiertem Zirkoniumoxid, allgemein bekannt als Transformations-Zähigkeits-Zunahme, ist in der Vergangenheit hinlänglich untersucht worden. Da das Transformationsverhalten der beiden Phasen von der Temperatur und der Spannung abhängig ist, ist ihr Transformationsverhalten in bezug auf ihre Umgebung, wie zum Beispiel beim Schneiden von Metallen, wo beides, Temperatur- und Spannungseffekte gleichzeitig auftreten, von Interesse. Obgleich jeder Arbeitsgang zu Transformationen und Phasenänderungen führen kann, gibt es über die Anwendung dieser Materialien noch keine Arbeit. Die vorliegende Arbeit befaßt sich mit der Herstellungstechnik von keramischen Schneidewerkzeugen, basierend auf Zeriumoxid stabilisiertem Zirkoniumoxid ohne dabei die Phase zu verändern. Das Verhalten dieser Werkzeuge bei der Bearbeitung von Gußeisen wird bestimmt, und ihr Transformationsverhalten beim Metallschneiden untersucht.

Le phénomène de transformation phase quadratique/phase monoclinique, susceptible de se produire au sein d'une zircone initialement stabilisée sous forme quadratique, et qui se traduit par un renforcement de la ténacité, a été largement étudié.

La transformation de phase est notamment fonction de la température ainsi que des contraintes éventuelles, si bien que le travail dans des environnements particuliers telle que la coupe de métaux, pour laquelle ces deux paramètres interviennent simultanément est d'un intérêt certain.

Puisque toute opération d'usinage peut conduire à des modifications de phase de la zircone, la littérature mentionne peu de cas de l'utilisation de ces matériaux dont le renforcement est basé sur le mécanisme de transformation de phase.

Le présent article se rapporte aux techniques de fabrication d'un outil de coupe en céramique à base de zircone stabilisée à l'oxyde de cérium sans destruction de phase.

Les performances en service de l'outil pour l'usinage de fonte sont évaluées et son comportement à la transformation lors de la coupe de métal est étudiée.

1 Introduction

Zirconia exists in three well defined polymorphs,[1] namely cubic (c) (above 2370°C), tetragonal (t) (between 2370 and 1150°C) and monoclinic (m) (below 1150°C). The high temperature phases can be stabilized to room temperature by the addition of dopants like calcia, magnesia, yttria and ceria. Depending on the nature and quantity of the stabilizer used, different types of stabilized zirconia can be attained. In general, calcia leads to a fully stabilized zirconia (FSZ) which is completely of cubic structure; yttria (above 3 mol%) and magnesia lead to partially stabilized zirconia (PSZ) containing t phase particles as precipitates in a cubic matrix;

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yttria (less than 3 mol%) and ceria (up to about 20 mol%) can lead to tetragonal zirconia polycrystals (TZP), consisting of single t phase structure.[2]

The stabilized high temperature t phase is in a metastable condition. It needs energy to transform to the more stable m phase. If a passing crackfront meets a t phase particle, the t particle will absorb energy[3] from the passing crack and transform to m phase with an associated volume expansion[4] of about 4%. This serves to retard the passage of the crack in two ways:

(i) by absorbing energy, thereby depriving the crackfront of that energy by virtue of which it could have propagated further and
(ii) by exerting compressive stresses (generated by the t to m transformation and associated volume expansion) against the passing crack, thereby preventing it from further propagation.

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]

Since transformation toughening is directly dependent on the t phase content and since TZP has 100% t phase, TZP materials are capable of developing very high toughness. Ceria and yttria are the two materials that can lead to TZP—i.e. yttria TZP (Y-TZP) and ceria TZP (Ce-TZP).

The disadvantage of Y-TZP is that it loses its strength (degrades) when annealed in the temperature range 200–300°C in humid air or at lower temperatures in water.[7] Such problems are not present in Ce-TZP, because it has a very good resistance to transformation during low temperature annealing.[8] This property has lead to the concept of doping ceria on the surface of Y-TZP specimens in order to improve the resistance to degradation during low temperature ageing of the bulk Y-TZP.[9]

2 Previous Studies

2.1 Fabrication

12 mol% ceria stabilized zirconia powder (TZ-12 Ce) was mixed with a suitable binder and cold pressed uniaxially at 200 MPa into square pellets. These were then sintered at 1350°C, for 2 h, in air to obtain 100% t phase structure.[10] The properties of these specimens were evaluated. The hardness was estimated using a Vicker's indentor at 10 kg load. Three point bending strength was estimated[11] from the breaking loads of rectangular samples (3·5 × 4·5 × 28 mm) with a span of 20 mm in a Universal testing machine (Carl Shenck, Germany) at a strain rate of 1 mm/min by using an expression.[12] Fracture toughness was evaluated[13] by indentation techniques[14] as well as single edge notch beam (SENB) techniques.[15] These values are tabulated in Table 1.

Table 1. Properties of Ce-TZP tool material

Phase structure	– 100% tetragonal
Hardness (H_v)	—882
Bending strength	—390 MPa (3 point)
Fracture toughness	—11 MPa m$^{1/2}$ (indentation)
	—9 MPa m$^{1/2}$ (SENB)
Density	—6·138 g/cc (99% theoretical density)

2.2 Grinding

Ce-TZP is highly transformable[8] and is known to transform even due to polishing. Transformations in zirconia are dependent on both temperature and stress. Stress is known to induce a t to m phase transformation[2] and temperature as in grinding is known to bring about an m to t phase transformation.[16] A detailed study on grinding of Ce-TZP was conducted.[17] These studies showed that at suitable combinations of grinding speed and depth of grinding, complete cyclic transformation (t–m–t) can occur.

2.3 Sliding friction

To assess the friction and wear characteristics in sliding contact with metal surface, the Ce-TZP samples were subjected to wear testing in a disc-on-disc type wear testing rig. It was observed that in such an environment also, both stress induced t to m phase transformation and temperature induced m to t phase transformation were possible.[18]

3 Suitability of Ce-TZP for Cutting Tool Applications

Cutting tools are subjected to very high temperatures and pressures.[19] In such an environment, tool wears or fails by one or more of several mechanisms like abrasive wear, chipping at the edge, thermal cracking, adhesion and seizure at interfaces, plastic deformation, oxidation, diffusion, etc. Hence tool materials should have improved physical, chemical and mechanical properties at elevated temperatures. Generally, ceramics are excellent heat-resistant materials retaining their mechanical properties at very high temperatures. Tool materials need to be simultaneously hard, tough and wear resistant.[20] In general, hardness and toughness are in opposition since higher hardness is usually associated with greater brittleness. Hence, there always has to be a compromise between the desired hardness and the necessary toughness, because improved toughness means less downtime to replace broken tools,[20] with reduced tool life.

In other words, the tool should be hard enough to penetrate the workpiece without suffering any undue deformation. Once this is achieved, the next requirement is to delay the crack propagation, i.e. to absorb more energy before fracture (FRS or fracture rupture strength).

The present material, Ce-TZP, has sufficient hardness (about three times that of the workpiece material, cast iron) to penetrate the workpiece material. It also exhibits large FRS by virtue of its fracture toughness as explained in the introduction. Hence, it was decided to test this material as a cutting tool.

From previous studies on Ce-TZP (Section 2), it was found that Ce-TZP could exhibit transformation toughening and cyclic transformation (t–m–t) under suitable combination of stress and temperature as in a grinding operation[17] or a wear environment.[18] Since metal cutting also involves stress and temperature effects,[19] Ce-TZP may be assessed for its performance as a cutting tool. However, it is to be noted that Ce-TZP is of low hardness compared to other ceramics (only around 880 H_v) as shown in Table 1.

4 Experimental Procedure

4.1 Fabrication details

Since any processing was found to induce transformations,[17,18] it is safe to avoid processing, as far as possible. In order to try Ce-TZP as a cutting tool insert, new dies were fabricated with sufficient allowance for sintering contraction, to get an as-sintered dimension of 12·7 mm (standard size for square inserts). These were sintered as explained in Section 2.1. However, nose radius (1·8 mm) had to be provided only by grinding. Again, from the knowledge gained from the grinding study, conditions optimal for inducing complete cyclic (t to m to t) transformation were used to grind the nose radius in an optical profile grinding machine. Figure 1 shows the tool bit before and after providing nose radius (the insert with nose radius is shown after machining). Table 2 lists the tool geometry used.

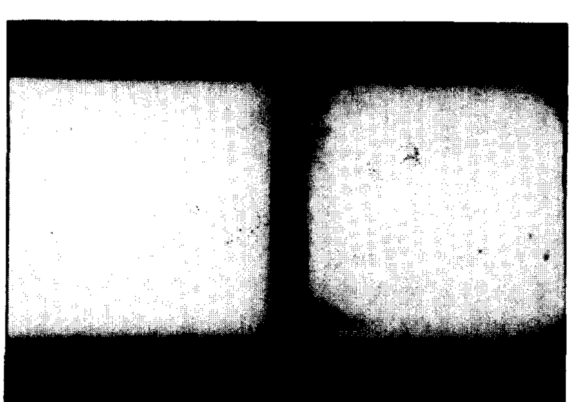


Fig. 1. Ce-TZP tool inserts.

Table 2. Tool geometry used

γ	α	λ	κ	θ	r
−6	5	−5	75	90	1·8

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

4.2 Performance evaluation

These inserts were used to cut spheroidal graphite iron (SG iron), (225 H_v), in a high-speed VDF lathe. This material was chosen because ceramics are generally used to machine cast iron[21] and also because of the fact that S.G. iron has enormous application potential in an increasing number of engineering components compared to the more traditional cast irons containing flaky graphite.[22]

Cutting velocities between 200 and 300 m/min were used with a constant feed rate of 0·063 mm/rev and a constant depth of cut of 0·75 mm. The flank wear on the tool was measured in a tool-maker's microscope. The forces during cutting were measured with the help of a Kistler dynamometer. The surface finish of the machined surfaces was measured using a perthometer. The wear pattern of the tool was studied using a scanning electron microscope (SEM). The chips were also analysed.

5 Observations

5.1 Cutting forces

The force pattern during machining with various cutting speeds at 1 min machining time is shown in Fig. 2. It can be seen that the forces are considerably less. This may be attributed to the low value of the depth of cut. It is also evident that the cutting speed range of 225–275 m/min is the critical speed range for the Ce-TZP tool, since the cutting forces remain constant in this range of speeds. Figure 3 shows the type of chips produced, at $V = 225$ m/min, $s = 0{\cdot}63$ mm/rev and $a = 0{\cdot}75$ mm, at 1 min machining time.

5.2 Tool wear

Figure 4 shows the flank wear growth with machining time. It can be seen that the value of 0·3 mm (for the width of flank wear land), which is considered to

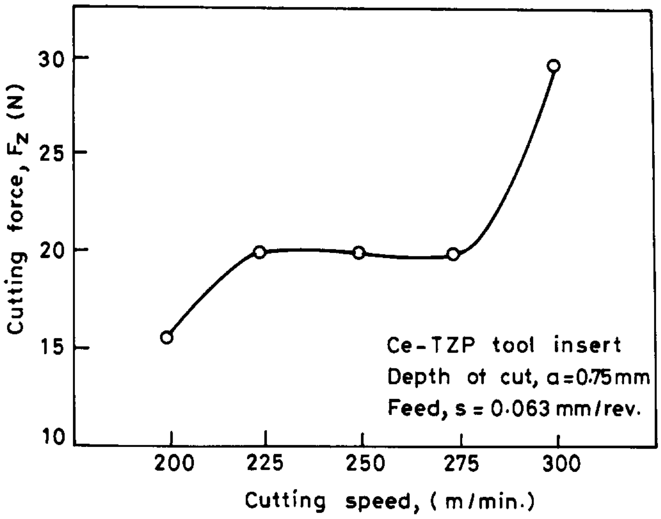


Fig. 2. Variation of cutting forces with cutting speeds.

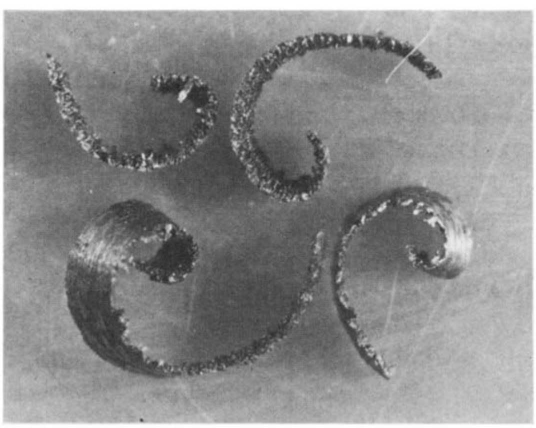


Fig. 3. Macrograph of chips obtained on turning cast iron with Ce-TZP tool.

be the limit for tool wear assessment,[23] is reached in about 4 min (for 225 m/min cutting speed). Table 3 lists the flank wear growth, with machining time, for various cutting speeds, at $s = 0{\cdot}063$ mm/rev and $a = 0{\cdot}75$ mm.

Figure 5 shows the SEM picture of the wear pattern on the tool tip and surface, of a tool insert after machining at $V = 225$ m/min, $s = 0{\cdot}063$ mm/rev and $a = 0{\cdot}75$ mm for 1 min. It can be seen that crater formation and edge depression are the predominant mechanisms of wear. The ups and downs marked by the striation like cracks on the vertical faces of the primary and secondary cutting edges are clear representations of the plastic deformation occurring in the Ce-TZP tool during machining.

Table 3. Flank wear growth of Ce-TZP tool bit (mm)

Cutting speed (m/min)	*Time (min)*				
	1	*2*	*3*	*4*	*5*
200	0·068	0·15	0·24	0·285	0·32
225	0·17	0·22	0·28	0·30	0·38
250	0·185	0·28	0·30	0·36	0·42
275	0·20	0·29	0·34	0·45	0·53
300	0·24	0·28	0·355	0·38	0·54

It was observed that the tool could perform satisfactory cutting even up to about 20 min, even after the flank wear had grown above 0·3 mm. It seems that the limit of 0·3 mm for flank wear for tool life considerations need not be applicable for the present tool since it performs well even up to a flank wear of 0·6 mm.

5.3 Machinability index exponent

The machinability index exponent, n, was calculated as follows:

By Taylor's Tool Life equation,[24]

$$VT^n = C$$

where:

V = cutting velocity for a given tool life in m/min;
T = tool life in min;
n = machinability index exponent;
C = constant.

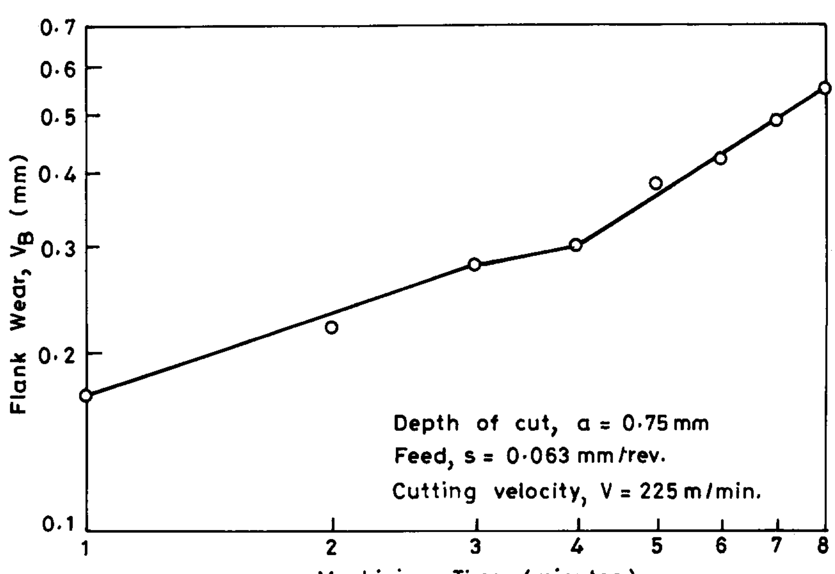
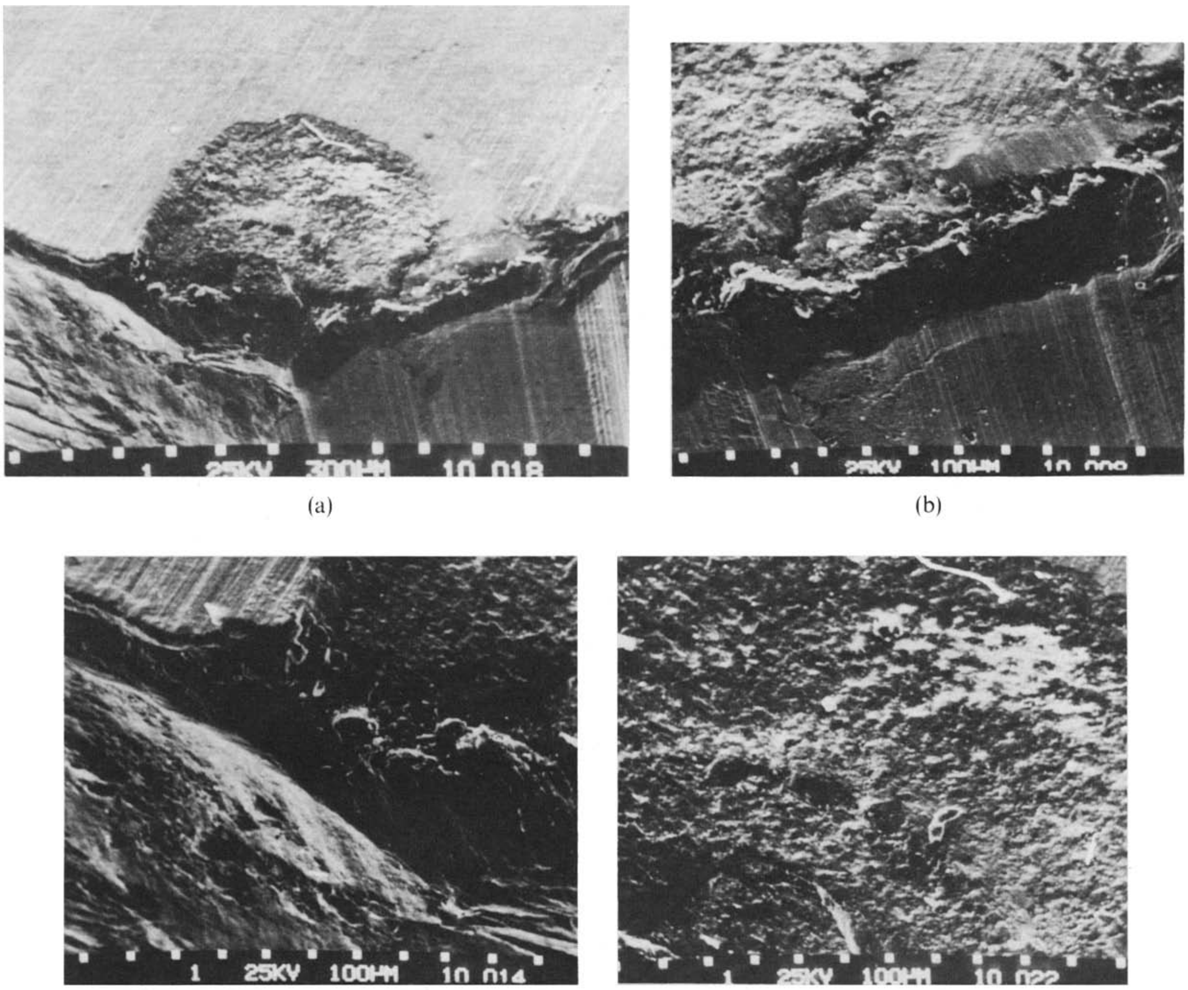


Fig. 4. Growth of flank wear with machining time.



(a) (b) (c) (d)

Fig. 5. Scanning electron micrographs of tool wear (a) nose (b) primary cutting edge (c) secondary cutting edge and (d) crater region (rake face).

For two different velocities, represented by suffices 1 and 2, it can be written as

$$V_1 T_1^n = C = V_2 T_2^n$$

or

$$(T_1/T_2)^n = (V_2/V_1)$$

$$n \log(T_1/T_2) = \log(V_2/V_1)$$

$$n = \frac{\log(V_2/V_1)}{\log(T_1/T_2)}$$

From Table 3, for a cutting speed of 225 mm/min, flank wear reaches a value of 0·3 mm in 4 min. For 250 m/min, flank wear of 0·3 mm is reached in 3 min. Using these values (cutting velocity and tool life) in equation for n,

$n = \log(250/225)/\log(4/3) = 0{\cdot}367$
$n = 0{\cdot}4$ on rounding off to the first decimal.

This value of $n = 0{\cdot}4$ is in agreement with any other ceramic tool.[25]

5.4 Surface roughness

Figure 6 shows the variation of the surface roughness (R_a) of the workpiece with machining time. The R_a value of the machined workpiece, cylindrically returning very close to 0·1 μm is an indication of the possible cyclic transformation at the tool tip.

5.5 Transformation during cutting

To assess the transformation during cutting, the tool tip was characterized by XRD,[26] both before and after machining. The XRD showed 100% t phase in both the cases. In order to assess whether any m to t phase transformation is possible, the conditions in optical profile grinding were suitably changed to induce m phase (due to grinding) at the tool tip (during grinding of nose radius). It was found that even this tool, having partly m phase at its tip, showed 100% t phase, after machining (at 225 m/min) for about 1 min. This shows that any m phase present at the tool tip is converted to t phase. Such a phenomenon is known to be indicative of cyclic transformation wherein the stress during cutting causes the t to m phase transformation and the frictional heat at the tool chip interface reverts the so formed m back to t phase.[27]

From the sliding friction between the ceramic–

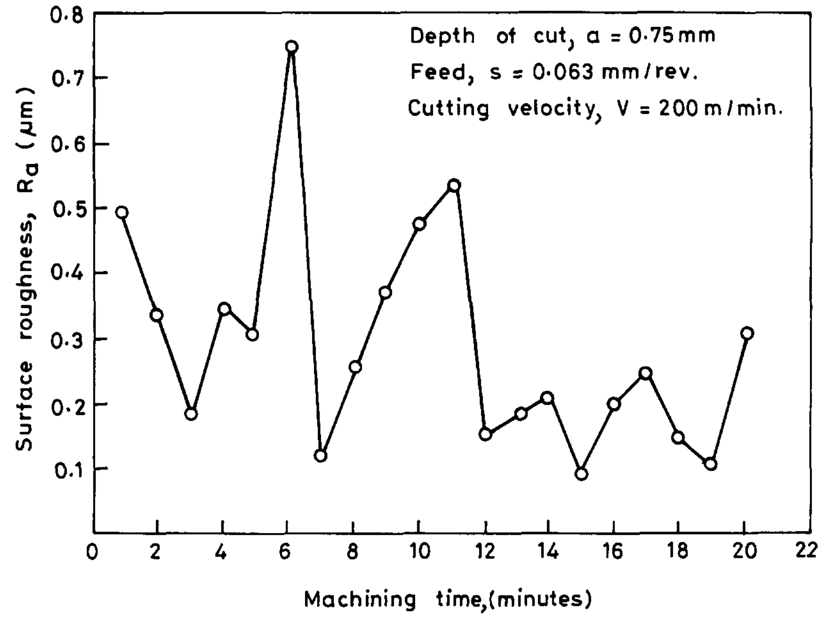


Fig. 6. Variation of surface roughness of workpiece.

steel interface, it has been observed that Ce-TZP exhibits cyclic transformation due to mechanical stress and frictional heat. Similarly, Ce-TZP could sustain its cutting ability due to cyclic transformation occurring over the cutting nose zone. This is possible because the temperature at the tool chip interface may be as high as 1000–1200°C.[28] At this temperature, only t phase is stable and hence any m phase produced due to the stress arising during cutting gets transformed back to t phase due to the frictional heat at the chip tool interface. Thus, it seems that the Ce-TZP tool bit is capable of exhibiting complete cyclic (t–m–t) transformation in a metal cutting environment, which facilitates transformation toughening, enhanced wedge retention and cutting performance. Similar transformation during cutting, have been reported by the authors in Yttria TZP (Y-TZP) tool also.[27]

6 Conclusion

Based on the present study, it may be concluded that Ce-TZP, in spite of its low hardness, can be efficiently used as a cutting tool insert for high speed turning/finishing by proper fabrication techniques. The newly developed tool seems to exhibit transformation toughening as well as cyclic transformation which appear to be the reason for the enhanced wedge retention and cutting performance.

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