Nanostructured Yttrium-Stabilized Zirconia/Alumina (YSZA) Cutting Insert for Machining High-Speed M1 Tool Steel

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Abstract
This research studies the performance of cutting inserts made of nanostructured yttrium-stabilized zirconia/alumina (n-YSZA) in machining of high speed M1 tool steel. This paper briefly describes the fabrication of the nanostructured YSZA cutting inserts and machining experimental procedures. After machining, the nanostructured cutting inserts are evaluated with scanning electron microscopy (SEM) and optical microscope, and compared with commercial ceramic cutting inserts under the same conditions.

Key words: Nanostructured materials; Cutting inserts; Machining.

1 Introduction
Due to their superior mechanical and chemical properties such as hardness, abrasive resistance, chemical inertness and high stability in high temperature, advanced engineering ceramics offer unique capabilities as tribological materials [1]. Advanced ceramics for tribological applications mainly include alumina (Al₂O₃), silicon nitride (Si₃N₄), silicon carbide (SiC), zirconia (ZrO₂) and SiAlON. One of the applications of these materials is cutting tools. Cutting tools made of advanced engineering ceramics have been applied to high-speed finishing operations and machining of difficult-to-machine materials. However, due to their high brittleness and relatively low fracture toughness, the extent of the application of advanced ceramics in cutting tools has been limited. Materials with fine microstructures have been recognized to exhibit technologically attractive properties. When the grain size of a material decreases to a scale of tens of nanometers, one obtains a novel class of materials, called “nanostructured materials” (n-materials), which possess microstructures and properties different from their conventional counterparts [2]. It has been known that both hardness and toughness can be enhanced by the reduced grain size and unique microstructures in n-materials [3]. Therefore, the performance of the cutting tools made of n-materials is expected to improve.

This research investigates the cutting inserts made of nanostructured yttrium-stabilized zirconia and alumina in turning of high speed M1 tool steel. After turning, the n-YSZA inserts are observed with a scanning electron microscope. Flank wear (VB) is measured with an optical microscope. For comparison, commercial alumina cutting inserts have been used in machining.

2 Experimental Procedures
Bulk n-YSZA was fabricated from its nanoscale powders. In the fabrication, a method called transformation-assisted consolidation (TAC) was used, which was similar to that for bulk nanoscale titania described by Liao et al. [4]. This method used high pressure and relatively low temperature in sintering to limit grain growth. The nanoscale grain size in powder is sustained under this condition and the density of the sintered materials is also enhanced.

The bulk n-YSZA was sliced and then ground with a diamond wheel on a high-precision surface grinder. The round corners of the cutting inserts were ground on a cylindrical grinder with a special grinding jig as shown in Fig. 1a. All the inserts were manually lapped and polished with diamond pastes to eliminate possible surface damage inherited from the previous grinding processes. The insert had dimensions of 12.7×12.7×4.8 mm (or ½×½×⅛ inches) and corner radius of 1.2 mm (or ⅛ inches), conforming to the ISO specifications of SNG433. Fig. 1b shows the 3D view of the inserts and Fig. 1c is the cutting tool insert-holder assembly.
The rake face of the as-made inserts was observed with SEM. The micrograph in Fig. 2a clearly shows two phases: alumina uniformly embedded in yttrium-stabilized zirconia. Due to the lapping and polishing processes, grinding marks are invisible for the n-YSZA insert compared to the commercial alumina insert shown in Fig. 2b.

The n-YSZA inserts were used to machine high-speed M1 tool steel at a depth of cut of 0.76 mm, a feed of 0.14 mm per revolution and a cutting speed of 330 m/min. Machining was in dry condition without lubrication. The machining conditions are summarized in Table 1. The tool holder was MSRN16-4D, which provided a 5° negative rake angle. The machining process was real-time monitored by a 3D force transducer. After machining, the inserts were observed with SEM to investigate wear mechanisms. Under the same machining conditions, the commercial alumina cutting inserts were used for comparison. Through the comparison, the differences in wear mechanisms between the nanostructured and commercial inserts were identified, which can provide valuable information for the manufacturing of nanostructured cutting inserts.

### Table 1 Machining Conditions

<table>
<thead>
<tr>
<th>Workpiece Material</th>
<th>M1 high speed tool steel</th>
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</thead>
<tbody>
<tr>
<td>Depth of cut</td>
<td>0.76 mm</td>
</tr>
<tr>
<td>Feed</td>
<td>0.14 mm/rev</td>
</tr>
<tr>
<td>Machining speed</td>
<td>330 m/min</td>
</tr>
<tr>
<td>Machining coolant</td>
<td>Dry</td>
</tr>
</tbody>
</table>

### 3 Results and Discussions

As stated above, this study was aimed at exploring the potential applications of nanostructured ceramics to cutting inserts. The performance of a cutting insert depends on its material properties and could be judged through its wear observations after machining. After 30 minutes of machining of high-speed M1 tool steel under the conditions in Table 1, both n-YSZA and commercial alumina inserts were observed with SEM for cutting edge wear and measured by the optical microscope for flank wear (VB).

Figures 3a and 3b show the overall pictures of the worn inserts. From the figures, it is observed that both inserts were severely worn down on their cutting edges. However, the n-YSZA insert had more severe wear than the commercial
alumina insert: deeper wear crater and wider flank wear land. Also, the worn rake face of the n-YSZA insert is rougher than that of commercial insert. Obvious chipping is observed on the cutting edge of n-YSZA insert.

A closer look at the worn rake faces of two inserts (Fig. 4) shows that both fracture and ductile flow are observed on the n-YSZA insert while only ductile flow is observed on the commercial alumina insert. Additionally, for the n-YSZA insert, fracture seems to be the dominant wear mechanism. Ductile flow formed needle structures, which increase the wear resistance, on the rake surfaces of both inserts. However, more and smaller needle structures are observed on the commercial insert than on the n-YSZA insert.

Ploughing combined with fracturing resulted in rough flank face with deep wear grooves on the n-YSZA insert, as shown in Fig. 5a. Attrition caused layer-by-layer material wear, and therefore smaller and slower flank wear for the commercial cutter. The average flank wear (VB) are compared in Fig. 6 for the inserts, from which it is found that under the same machining conditions, the n-YSZA insert had more severe flank wear.

4 Conclusions
The cutting inserts of n-YSZA have been evaluated in machining high speed M1 tool steel, and are found to be inferior to the commercial alumina inserts. Nevertheless, this research is the first attempt to apply n-materials to cutting inserts. Further investigations are needed.

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References


![Fig. 5 Flank wear observation.](image)

![Fig. 6 Average flank wear (VB) comparison](image)