Dry turning of hard 2379 steel using a ZTA5Ce0.7La ceramic cutting insert: A study

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Abstract. The aim of this work is to evaluate the dry turning ability of zirconia toughened alumina reinforced with 5 wt.% CeO₂ and 0.7 wt.% La₂O₃ (ZTA5Ce0.7La) ceramics as cutting insert in turning of 2379 steel with hardness of 43 HRC. Triangular cutting inserts were fabricated using this material composition via powder metallurgy route. Results of the cutting insert were measured based on the average width of flank wear and surface finish of machined workpiece. Results show that the tool was able to machine tool steel and good surface finishes were obtained for most of the cutting speeds used in the machining test, except for the highest cutting speed of 237.5 m/min. The longest life (12.5 minutes) of the cutting inserts according to the measured flank wear for the turning at cutting speed of 87.1 m/min with considerably good surface finish (Ra of 0.778 µm). Therefore, this ZTA5Ce0.7La cutting inserts is possible to be used as a successful dry turning process of 2379 steel.

1. Introduction

The turning operation is an important metal removal process in the manufacturing industry, with many technological advancements such as Computer Aided Design/Manufacturing (CAD/CAM), Computer Numerical Control (CNC), high-speed machining and cutting tool technology. In general, the turning process uses single point cutting tool. In machining steels, insert or tip tool regularly used as a cutting tool. It is consists of a small piece of material which is brazed, screwed or clamped on to another body. Many factors related to the turning process, such as the resultant quality of machined surface and the economy of machining, greatly depend on the condition of the cutting tool, such as the magnitude of the worn tool. The wear on the cutting tool is the result of the friction between the cutting tool and the material being machined [1]. This wear reduces the sharpness of the tool tip, thus creating wear-related problems [2,3]. The factors such as hardness, wear resistance, fracture toughness and chemical inertness are known to affect the performance of a cutting tool while machining hard metal [4].
In recent years, a lot of studies focused on developing insert as a cutting tool for optimal performance in machining. The insert must possess good mechanical properties for example high hardness and fracture toughness which are crucial properties for cutting tool to withstand during machining of hard metals [2,5]. Therefore, studies related to the use of tools and its wear are indispensable during development of any enhanced cutting tool material. Dealing with hard metal such as EN24 steel with hardness HRC 40 to HRC 45, Senthil Kumar et. al discovered that adhesive wear of zirconia toughness alumina (ZTA) tool was lower than Ti[C, N] mixed alumina ceramic but the latter cutting tool produced better surface finish at machined workpiece [6]. Some of the materials which are already being used for cutting tool inserts are alumina based ceramics (Al$_2$O$_3$), cemented carbides, and cubic boron nitride (CBN) [7,8].

Refinements into the tool material compositions includes the inclusion of additives to further increase their mechanical properties. Many researchers have found that the inclusion of yttria stabilized zirconia (YSZ) and oxide particles into the alumina matrix could significantly increase the hardness and fracture toughness properties of alumina cutting tools [5,8–13]. However, there are scarce reports about the performance of ZTA ceramics as cutting insert for turning applications. The turning process of steel normally involves the utilisation of cutting fluids, which subsequently cause to negative ecologic, health impacts and environmental [14,15]. Thus, the dry environments should be considered in sustainable machining, which are beneficial in terms of environmental control and reducing machining cost. The selection of cutting insert materials is a crucial task for dry turning tool steel and give a major impact on wear and mechanical properties.

Therefore, this study focused on evaluating the ability of fabricated insert from improved composition of zirconia toughened alumina reinforced with 5 wt.% CeO$_2$ and 0.7 wt.% La$_2$O$_3$ (ZTA5Ce0.7La) ceramic composite for dry turning process. This composition proved to have harder and sustainable high fracture toughness by Dilshad et. al [12]. For this purpose, the performance of ZTA5Ce0.7La as cutting tools insert in turning 2379 steel was assessed according to the wear magnitude at flank area of the tool by using suitable microscope. The surface roughness value of the new generated surface of the workpiece was assessed by surface roughness tester.

2. Methodology and experimental procedure
The works of this study were divided into two parts. First part mentioned about preparation of the raw materials and methods of works used to produce insert from ceramic powders. Second part of this study explained the works for turning operation to evaluate the dry turning ability of ceramic cutting tool.

2.1 Insert Preparation
In this study, starting powders used were highly pure Al$_2$O$_3$ (Alcoa, A16SG, 99.9%), 5.4 mole% Y$_2$O$_3$ stabilized ZrO$_2$ (YSZ, Goodfellow), CeO$_2$ (Sigma Aldrich, 99.9%) and La$_2$O$_3$ (Sigma Aldrich, 99.9%). ZTA mixture was prepared from 80 wt.% Al$_2$O$_3$ and 20 wt.% YSZ as the main composition where the ratio between Al$_2$O$_3$/YSZ is consistently fixed at 4:1 to ensure its optimum mechanical properties [16]. Later, the exact amount for both CeO$_2$ (5 wt.%) and La$_2$O$_3$ (0.7 wt.%) was added to this ZTA composition to achieve excellent hardness and toughness properties of this composite [12]. Then, the powder was mixed in a ball mill for 24 hours via wet milling method. Once completed, the mixtures were dried in an oven at 95 °C and the obtained cake was poured then crushed into fine powders. The powder was pressed at 10 MPa for 2 minutes into triangle shape inserts (Figure 1) using a hydraulic press (Specac GS15011, USA). Subsequently, the resultant green bodies were sintered in air atmosphere at 1600 °C for 4 hours with 5 °C/min sintering rate in a high temperature electrical furnace (Lenton UAF18/5, United Kingdom).

The sintered inserts were evaluated for hardness and fracture toughness using simple indentation techniques (Shimadzu Vickers hardness tester HSV-20, Japan). The values of hardness were discovered using Vickers indentation technique (indentation load of 30 kgf for 15 seconds) measured by adequate indentation on the insert surface. The crack lengths as the result of indentations were
measured via a fabricated optical microscope by Shimadzu Vickers hardness tester (HSV-20) using the technique of straight-line method. The average value of hardness was calculated based on the average of five measurements, calculated based on the formula of Palmqvist crack proposed by Niihara [17]:

\[ 3K_{lc} = 0.035(Ha^{1/2})(3E/H)^{0.4}(l/a)^{-0.5} \]  

Where:
- \( K_{lc} \) = value of fracture toughness,
- \( l \) = length of the diagonal,
- \( a \) = Vickers diagonal half-length value (\( \mu m \)),
- \( H \) = value of Vickers hardness,
- \( E \) = Young modulus value of the sample,
- \( c \) = radial crack size length value (\( \mu m \)).

The fracture toughness (\( K_{lc} \)) was measured by Niihara equation.

2.2 Machining parameters and experimental procedures

The turning experiment conducted follows the ISO 3685 cutting conditions (Rev 2017) procedures [18]. Table 1 lists the complete tooling and cutting parameters applied in the experiments. The cutting tools were fabricated based on ISO standard designation of turning insert: TNGN 160408 FN. Figure 1 shows the triangular shaped inserts used, having 9.525 mm diameter inscribed circle and thickness values of 4.6 mm, which are screw-clamped into the tool holder (CTRNR 2020 K3). The combination of the tool holder and insert lead to 75° approach angle when the insert contacts the workpiece.

**Table 1. Tool and cutting parameters**

| Cutting Parameters       | Values                      |
|-------------------------|-----------------------------|
| Rotation speeds, N      | 660, 870, 1400 and 1800 rpm |
| Cutting speeds          | 87.1, 114.8, 184.7 and 237.5 m/min |
| Feed rate               | 0.11 mm/rev                 |
| Depth of cut            | 0.2 mm                      |
| Cutting length          | 100 mm                      |

**Figure 1. Triangle-shaped insert used throughout the turning experiment**

The workpiece selected is a high chromium 2379 steel cylinder bar measuring 300 mm in length and 42 mm in diameter. The average hardness value obtained for workpiece was 42 HRC. Table 2 shows the chemical composition of the tool steel workpiece material [19]. The turning experiments were performed in dry cutting environments on a JET GH-1860ZX lathe machine.
The tool life criteria is selected based on ISO 3685 [18], which is defined as the average flank wear (VB) width reaching 0.3 mm. The flank wear images were captured using a digital simple microscope (Shenzhen Hot Electronic Technology, HD-500X). An image analysis software (Image J) was utilized to measure the average values of VB. The flank wear measurement was taken immediately after every single cutting pass, equivalent to approximately 100 mm of cutting length. The surface roughness values of the machined workpiece were measured using a roughness tester (Mitutoyo SJ–410) up to a maximum average roughness, R_a, of 1.6 µm as indicated by ASME B46. 1-2009. The surface roughness was measured once the average flank wear width of the worn tool insert exceeded 0.3 mm.

### Table 2. Chemical composition of 2379 steel

|   | C  | Si  | Mn  | P   | V   | Cr  | Mo  | S   | Fe  |
|---|----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.5%| 0.1%| 0.15%| 0.03%| 0.9%| 11.0%| 0.6%| 0.03%| Balance |
| 1.6%| 0.4%| 0.45%| 1.1%| 12.0%| 0.8% |

3. Results and Discussions

The add-on of 0.7 wt.% La_2O_3 into the ZTA5Ce matrix resulted in a hardness value of 1703HV. While for fracture toughness, the value obtained was 8.20 MPa.m^{1/2}. These obtained results are slightly lower than those reported by Dilshad et. al [12] for the same amount of La_2O_3 additions. However, the previous work had used a higher compaction pressure during the preparation of the powder compacts [12]. A higher compaction pressure would improve mechanical properties by lowering the level of porosity in the specimen compared to uniaxial press method [20,21]. Furthermore, it has been reported that the reduction of porosity in the microstructure is a major contributor in the increase of hardness values [22,23]. Thus, decreasing the porosity in the microstructure would increase its resistance to the applied load of the indentation test.

The tool life criteria is taken as an indicator for the cutting insert performance. It is based on the ISO 3685 Standard which defined a boundary value of average width of flank wear (VB) at 0.3 mm. Increasing the hardness and fracture toughness of these ceramic inserts prevent premature failure or rapid plastic deformation occurring throughout the machining process. The increase of flank wear over time for different cutting speeds are shown in Figure 2. In general, the flank wear increases systematically against machining time. From the figure, clearly seen that the ceramic tool life for the machining of hard material is reached within 7 minutes for most of the cutting speeds investigated, characterised with a steady increase of flank wear. However, when machined with the highest cutting speed available at the lathe machine (237.5 m/min), the tool experiences rapid tool wear within 3 minutes of machining time. This is believed to be caused by the vibrations of the machine, which was operated at its maximum spindle rotation [24,25].
Figure 2. Average flank wear for various cutting speed against machining time

Figure 3 shows the flank wear images captured using the digital microscope and analysed in the image analysis software (Image J). All images were taken after the average width of $V_B$ has exceeded 0.3 mm. As expected, abrasive wear mechanism was observed to be dominant on the flank area for most of the cutting tools measured. Figure 3 (a)-(c) clearly shows a smooth abrasive wear with a relatively low signs of scratches. No reactions were observed on the steel workpiece as the ceramic tool (alumina) was stable at high temperatures, thus no other wear mechanism, such as diffusion wear, was observed. These observations are similar to those reported by Sobiyi et al. [26] on their use of ceramic tools while machining martensitic stainless steel. For the highest machining speed of 237.5 m/min, the tool experienced excessive chipping and was distorted completely from the original tool geometry. Typically, the progress of wear would begin with abrasion wear, which will the accumulate and finally causing adhesion wear at the end of machining, as illustrated in Figure 3 (d).
Figure 3. Flank wear image captured by digital microscope at various cutting speed (a) 87.1 m/min, (b) 114.8 m/min, (c) 184.7 m/min, and (d) 237.5 m/min.

Good surface roughness values of the machined workpieces were obtained for most cutting speeds although the workpieces were examined after average width of $V_B$ of the inserts has exceeded 0.3 mm. As illustrated in Figure 4, only the surface roughness value obtained for the cutting speed of 237.5 m/min was over the acceptance limit of average roughness, $R_a$ (1.6 μm). This was expected as the tool has catastrophically failed and has damaged the machined surface.

Figure 4. Surface roughness of the workpiece gained at all cutting speeds

4. Conclusion

In this study, ceramic tool inserts made from a composition of ZTA reinforced with cerium (IV) oxide and lanthanum oxide (ZTA5Ce0.7La) was evaluated for the turning of hard workpiece. It is proven that ZTA5Ce0.7La ceramic cutting inserts was successfully turning the hard metal 2379 steel. The following conclusions are made from the discoveries of this study:

- The cutting speed has major influence on the flank wear rate. Increasing the cutting speed will correspondingly increases the flank wear.
- The best insert performance was attained for the cutting speed of 87.1 m/min, with a tool life exceeding 12 minutes.
• The worst cutting performance was obtained at a cutting speed of 237.5 m/min.
• The failure of the inserts is predominantly by abrasive wear, although excessive tool chipping may occur at higher cutting speeds.
• Good surface roughness values for the machined workpiece surfaces were obtained for most cutting conditions, except for the highest cutting speeds. At the highest cutting speed, the excessive tool wear/chipping has impaired the machined workpiece surface.

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