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Friction Comparison and Wear Analysis of Ceramic Cutting Tools Made from Alumina-Zirconia-Chromia Content

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ABSTRACT

This research focused on wear analysis by using the coefficient of friction (COF) and high-speed CNC turning machine against ceramic cutting tools made from 80 wt.% Al_2O_3 - 20 wt.% ZrO_2 mixed with 0.2 - 0.8 wt.% Cr_2O_3. The results showed that the sample with a composition ratio of 80 wt.% Al_2O_3 – 20 wt.% ZrO_2 – 0.6 wt.% Cr_2O_3 demonstrated the lowest coefficient of friction of 0.305. In terms of tool wear, this cutting tool showed uniform abrasion marks on the flank wear, resulting in 60% - 80% better tool life compared to Al_2O_3 and Al_2O_3- ZrO_2. Based on the observation by using SEM, analyses showed that grains were tightly bound to each other at a high cutting speed of 350 m/min and with a feed rate of 0.175 mm/rev, compared to Al_2O_3 and Al_2O_3- ZrO_2 which showed visible chipping and notch. The addition of 0.6 wt.% Cr_2O_3 on Al_2O_3-ZrO_2 composition was enough to increase the strength and reliability against ceramic cutting tools for machining purposes.

1. Introduction

The ceramic materials have been widely used in cutting operations is Al_2O_3 because of its advantages, such as excellent chemical stability and high hardness, making it suitable for industrial applications like cutting steel and cast iron (in order to get a better surface). The excellent features of Al_2O_3-based ceramic make Al_2O_3 a reliable choice for machine engineering metals and commonly-used material at high temperatures, as compared to high-speed steel and carbides [1]. However, solid Al_2O_3 has low toughness and strength, which lead to thermal cracking and work piece damage. Limitations of the mechanical and physical properties of Al_2O_3 can be improved by mixing it with additional materials, such as ZrO_2, silver, and yttria stable ZrO_2 (YSZ) [2].

The addition of ZrO_2 aims to improve some of the weaknesses in the Al_2O_3 structure, which can further strengthen ceramic cutting tools. Roy *et al.,* [3] studied the minimum content of ZrO_2, which

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is below 20% to 25%, that can produce a strong ceramic cutting tool with better abrasion resistance than pure Al_2O_3. High ZrO_2 content in an Al_2O_3 structure increases the fracture resistance up to 50% [4]. ZrO_2 also acts as a barrier to the increase in Al_2O_3 grain size during the sintering process, so that the grain size on the cutting tool is not too large. This is important because a large grain size can cause ceramic cutting tool failure. One of the powerful mixtures and additives to Al_2O_3 used for ceramic cutting tools is Cr_2O_3, which is a new discovery in the development of cutting tools [5] and according to Azhar *et al.,* [6], when it is added to Al_2O_3, it provides fracture toughness due to the formation of solid solution isovalent.

In order to produce high-quality products, the parameters of the machine are crucial factors that need to be considered. The main parameters are cutting speed, feed rate, and depth of cut. In contrast, the brittle-ductile regime occurs when the cutting speed is increased. This happens because the material is too soft at high temperature [7,8]. Generally, proper selection of cutting parameters is essential to produce high-quality products at low cost because the advantage of cutting parameters is that they may increase productivity, but the disadvantage is that they may impair the surface finish quality and tool life.

The above-mentioned studies proved that the various compositions of ceramic powder can be used as a cutting tool in high-speed machining. In the present study, wear performance of ceramic cutting tool was investigated by the addition of various Cr_2O_3 weight percentages (wt.%) against Al_2O_3-ZrO_2 by using a tribology test with high-speed machining. Tool life, wear mechanism, and tribology were measured to relate the compositions of ceramic powder. This study is a continual update from previous research from Norfauzi *et al.,* [8] in term of Al_2O_3-ZrO_2-Cr_2O_3 composition.

2. Methodology

This work aims to identify the tool wear of fabricated ceramic cutting tools. The experiments for wear identification were carried out by using tribology test and CNC Turning Machine (HAAS SL-20). The medium is carbon steel AISI 1045, which is commonly used in machine industry for the production of parts such as shaft, gear, and pin, was selected as the material for machining process. The chemical composition and mechanical properties of AISI 1045 are shown in Table 1.

Table 1
Chemical composition and mechanical properties of AISI 1045 steel

Chemical composition (%)							
G	Si_{max}	S_{max}	P_{max}	Mn	Cr_{max}	Cu_{max}	Ni_{max}
0.42–0.5	0.4	0.045	0.04	0.5-0.8	0.3	0.3	0.4
Mechanical characteristics							
R_e [MPa]		R_m [MPa]		As (%)			HB
305		580		16			250

2.1 Sample Preparation

The mixing process of ceramic compositions is done by using a dry method. Each composition is weighed evenly with a 4-gram then placed in a jar and mixed evenly using a ball milling machine for 12 hours with 40 rpm rotation speed. In addition, ball mill is also used to produce a finer and uniformly powder mixture. The powder is then, poured into a mould and compacted using a mechanical press and press up to 5 tons to get the determined shape of green bodies. To obtain a compact ceramic body, by using a cold isotactic press (CIP) machine, the ceramic body is compacted up to 300 MPa for 30 seconds. Then, the ceramic body is sintered up to 1400 ^oC and 9 hours to obtain a strong and compact ceramic body. Figure 1 shows the process of fabricate ceramic cutting tools. Tribology tests were conducted using the coefficient of friction (COF) method to determine the surface strength of the cutting tools. They are measured according to the standard determined by ASTM C1028. The COF tests were performed to obtain the lowest friction results from different wt.% Cr_2O_3 content of 0.2 wt.% - 0.8 wt.% against 80 wt.% Al_2O_3 - 20 wt.% ZrO_2. Table 2 shows the parameters used for the COF.

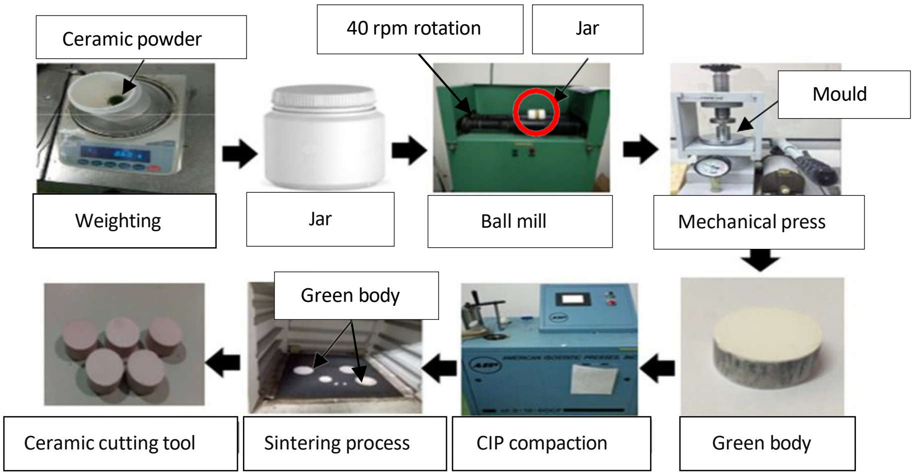


Fig. 1. Ceramic cutting tool process development

For machining, evaluation tests were carried out on AISI 1045 carbon steel using various types of fabricated ceramic cutting tools at various cutting speeds and feed rates as shown in Table 3. Machining tests were performed according to ISO 3685 standard, where the cutting tool was tested up to 0.3 mm average flank wear (*Vb* avg) reading to determine the performance of each cutting tool [9]. For each machining trial, the measurement was made periodically according to the cutting length of AISI 1045 bars. For each measurement, the image of the observed tool wear was captured by using a digital camera.

Table 2
Parameter of tribology machine for COF test

Parameters	Setup number
Set load	10.0 N
Set stroke	3 min
Set velocity	3 mm/sec
Test time	1800 sec

Table 3
Machining parameters in this work

Parameters	Details
Cutting tool	Al_2O_3, Al_2O_3-ZrO_2, Al_2O_3-ZrO_2-Cr_2O_3
Cutting length	210 mm
Diameter AISI 1045	40 mm
Depth of Cut	0.5 mm
Feed rate (mm/rev)	0.10, 0.125, 0.150 and 0.175
Cutting speed vs. spindle speed	300 m/min = 2387 rpm 350 m/min = 2784 rpm

3. Results

3.1 Coefficient of Friction (COF)

Figure 2 shows the effect of a mixture from various wt.% Cr_2O_3 on a specific mixture of 80 wt.% Al_2O_3 and 20 wt.% ZrO_2. The most ideal mixtures between Al_2O_3-ZrO_2 was 80 wt.% and 20 wt.%, respectively [8]. It can be seen that COF started from zero and rapidly increased until it reached a point stability. During the running in these phenomena, the surface topography changed, a chemical reaction took place until the system achieved a steady state. This figure also shows an additional of 0.6 wt.% Cr_2O_3 recorded the lowest friction result of 0.305. Compared to 0.2 wt.% and 0.8 wt.%, which consistently showed a weak sample surface which recorded friction results of 0.46 and 0.55, respectively. However, on a sample of 0.4 wt.% Cr_2O_3 showed a deterioration and defect on the graph where the friction rate increased significantly. The reason for friction to arise was that the molecules on the sample surfaces bonded and resisted when they tried to move away and break the bonds [10]. This resulted in the change in the area of the contact surface and an increase in fluctuation of the curve. Shi *et al.,* [11] found that when the surface layer of the ceramic cutting tool for friction test was destroyed, the wear layer (located in the lower zone) of the worn surface started to take part in the rubbing process between the pin on disk and the debris of ceramic surfaces. This because of, due to the presence of porosity on the surface of the samples at 0.4 wt.% Cr_2O_3.

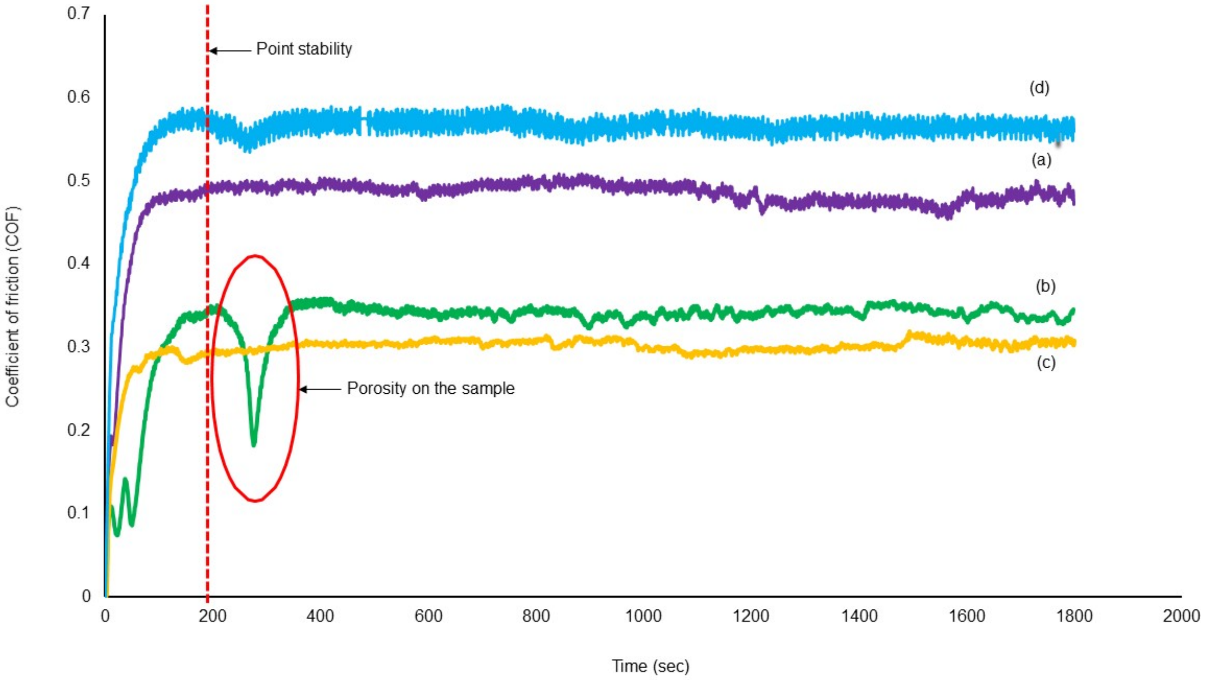
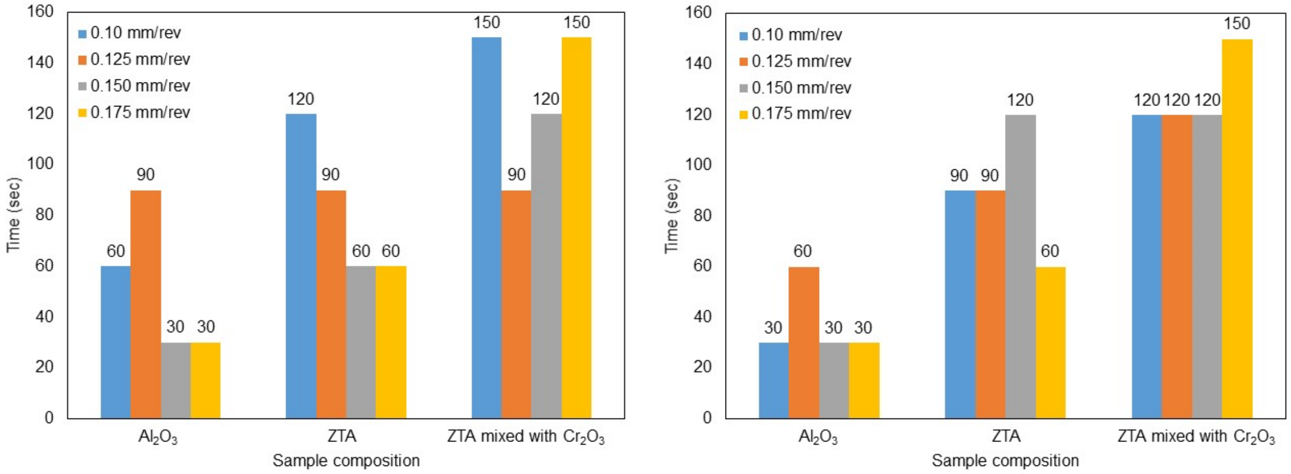


Fig. 2. Coefficient of friction (COF) versus time with different Cr_2O_3 contents: (a) 0.2 wt. %, (b) 0.4 wt. %, (c) 0.6 wt. % and (d) 0.8 wt. %

3.2 Tool Life

The ceramic content has the heat resistant property that overcomes the temperature generated by friction between the cutting tool and raw material. Figure 3 (a) shows the comparison of tool life with high cutting speed of 300 m/min and Figure 3 (b) shows the tool life of the cutting tools at a cutting speed of 350 m/min. The addition of Cr_2O_3 to Al_2O_3-ZrO_2 further strengthened the cutting tool at the highest feed rate of 0.175 mm/rev, the Al_2O_3-ZrO_2-Cr_2O_3 cutting tool lasted for 150 seconds has recorded 80% longer than Al_2O_3 and 60% better than Al_2O_3- ZrO_2 in term of tool life. When Cr_2O_3 is added into Al_2O_3, isovalent solid solution will form over the full range of compositions due to the fact that both Cr_2O_3 and Al_2O_3 are sesquioxides and have the same corundum crystal structure with similar lattice constants and the same atomic packing model [6]. Solid solution makes Cr_2O_3 evaporate and diffused, then coating the surface of the cutting tool [12], and it shows the Cr_2O_3 layer on the cutting tool is able to withstand friction and improve machining reliability. Besides that, the cutting speed affects the tool life of ceramic cutting tools more than the feed rate does [13]. However, feed rate studies also need to be stressed, according to Norfauzi *et al.,* [8] found that other than high cutting speeds, the feed rate also affected the cutting tool which can cause damage, such as chipping and notches, when machining carbon steel AISI 1045.



(a) (b)

Fig. 3. Comparison of tool life at cutting speed of (a) 300 m/min and (b) 350 m/min

3.3 Wear Mechanism

Figure 4 shows wear characteristics that were dominated by adhesive wear, chipping, and flaking. Chipping and flaking were obviously visible at the cutting edge of ceramic cutting tools, while, adhesive wear could be clearly seen through the colour change between the ceramic cutting tool and the adhesion of molten metal. The existence of molten metal attached to the end of ceramic cutting tool, called adhesive wear, could be clearly seen due to differences in the characteristics of material [8]. The concept of adhesive wear is based on the notion that adhesion occurs between asperities when they touch, followed by plastic shearing of the tips of softer asperities which then adhere to the opposing surface, and finally, separate as wear debris particles when machining is continued [14]. The high surface energy results in a high adhesive wear rate, as adhesive forces are higher for high surface energy [15].

The wear characteristics of Al_2O_3-ZrO_2 cutting tools, as shown in Figure 5, display clear abrasion marks and a more improved material than Al_2O_3. However, there are a few notches, chipping, and built-up edge (BUE) on the cutting edge when cutting speed was increased to 350 m/min. The abrasion marks occurred when hard particles on the raw material chip passed through the cutting tool face, and the abrasion marks were more predictable and thus, it can provide a stable tool life [15]. Notch and chipping showed the evidence of the fragility of the fabricated cutting tool, in which the strongly bonded grains slipped on each other (Al_2O_3- ZrO_2), and then the cutting end broke when the load was applied to the rotational impact. Notch wear occurred as a result of a strong rotational impact of the material against a cutting tool resulting in the formation of a V shape at the end of the cutting tool or flank face [8]. This exposed space formed in the notch effect was trapped by the molten steel.

Clear parallel lines at abrasion marks, as shown in Figure 6, indicated that the cutting tools could withstand and absorb impact and forces imposed by rotational impact between cutting tools and AISI 1045. The abrasion marks occurred when hard particles on the raw material chip passed through the cutting tool face. These abrasion marks were more predictable and thus, provide a stable tool life [15,16]. The tips of both cutting tools were more stable than Al_2O_3-ZrO_2 at the same cutting speeds and showed that the addition of Cr_2O_3 to Al_2O_3-ZrO_2 provided additional strength on the cutting tool without chipping and notches, even at high cutting speeds and feed rates [17,18]. The addition of Cr_2O_3 to the ceramic mixtures provided resilience, wear resistance, increased hardness and corrosion resistance [2,19,20].

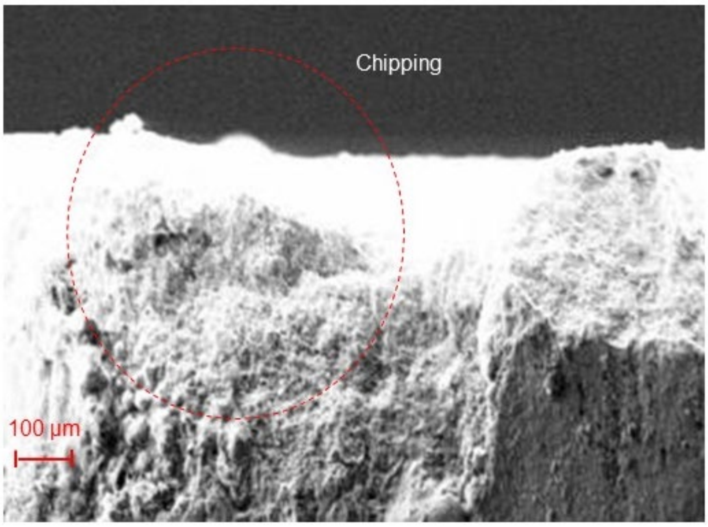


Fig. 4. Chipping on cutting point at 350 m/min cutting speed and feed rate of 0.175 mm/rev at Al_2O_3 cutting tool

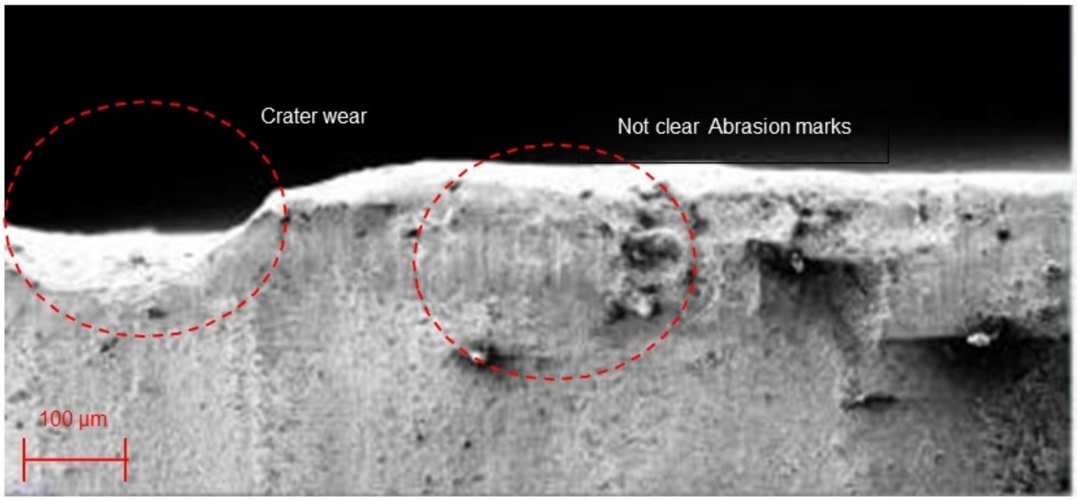


Fig. 5. Crater wear side of cutting point at 350 m/min cutting speed and feed rate of 0.175 mm/rev against Al_2O_3-ZrO_2 cutting tool

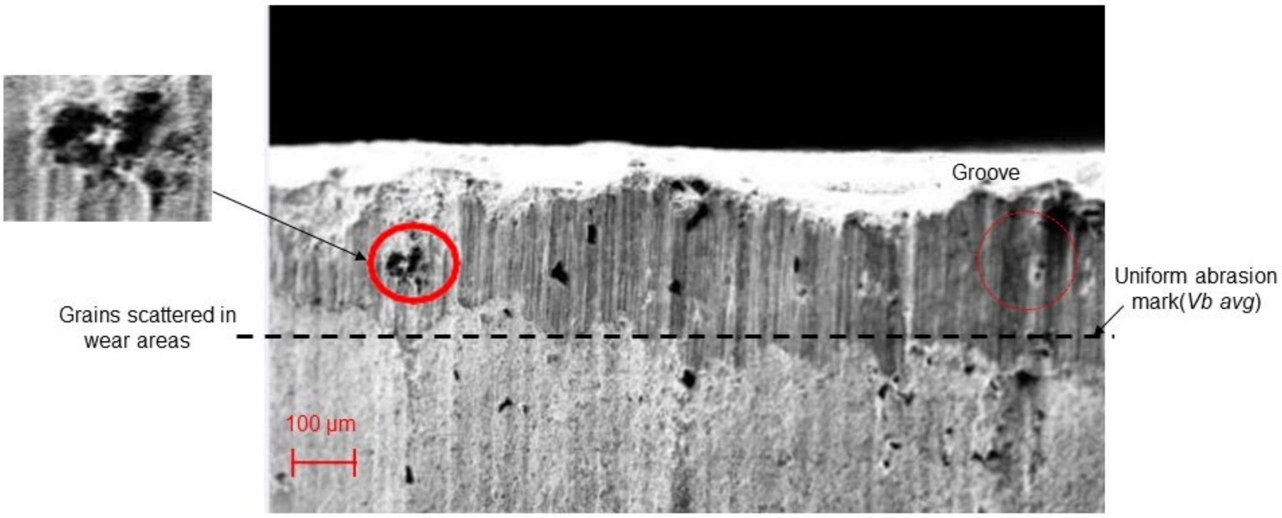


Fig. 6. Groove and parallel boundaries formed on Al_2O_3-ZrO_2 mixed Cr_2O_3 at cutting speed 350 mm/min and feed rate 0.175 mm/rev

4. Conclusion

The Al_2O_3-ZrO_2-Cr_2O_3 cutting tool produces better COF and machining performance compared to Al_2O_3 and Al_2O_3-ZrO_2. Concluding analyses of the investigation are as given below:

i. 80 wt.% Al_2O_3 – 20 wt.% ZrO_2 – 0.6 wt.% Cr_2O_3 demonstrated the lowest coefficient of friction of 0.305. In term of machining performances, the abrasion marks could be seen clearly and uniformly without any significant defects such as chipping, flaking, or notches. It shows the Cr_2O_3 layer on the cutting tool is able to withstand friction and improve machining reliability.
ii. Al_2O_3-ZrO_2 showed a slight disadvantage, where uneven abrasive marks were formed, and the tip of the cutting tool showed large chipping and notches.
iii. Al_2O_3 cutting tool produced the lowest performance and did not seem to have any abrasion marks on the cutting tool.

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