EFFECT OF HYDRAULIC PRESSURE ON HARDNESS, DENSITY, TOOL WEAR AND SURFACE ROUGHNESS IN THE FABRICATION OF ALUMINA BASED CUTTING TOOL

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ABSTRACT: Cutting tools can be considered major industrial necessities as it applied mostly to machine components. Development of self-fabricated cutting tool can facilitate lower machining cost as long as the cutting tool can perform effectively. This paper presents the effect of hydraulic pressure on density, hardness, wear performance and surface roughness during fabrication of the alumina based ceramic cutting tool. Specific raw of alumina powders were ball milled compacted into green body using hydraulic press with different pressures of 6, 7, 8 and 9 tons. These green bodies were sintered at 1700°C in 4 hours soaking time. Hardness and density of sintered bodies were examined in order to correlate the effect of hydraulic pressure on mechanical properties. The samples were further tested into machining with AISI 1045 in order to evaluate their wear performances and surface roughness. The results show that density and hardness increased as the hydraulic pressure increased. The highest pressure of 9 tons demonstrated highest density and hardness of 2.77 g/cm^3 and 86.1 HRA respectively. The fabricated cutting tool capable to cut the AISI 1045 steel with the minimum wear rate recorded at 0.0025 mm/s for 9 ton of pressured sample. In terms of failure modes, the cutting tool suffered with abrasive wear and cracks at the edge of tool nose radius. Surface roughness demonstrate minimum 1.24 μm for 7 ton of pressure, which considered high for short time machining process. Overall, the self-fabricated cutting tool capable to cut the steel without catastrophic failure which demonstrated promising results to be improved in the future.

KEYWORDS: *Alumina Cutting Tool; Pressure; Hardness; Density; Machining*

1.0 INTRODUCTION

Cutting tools can be considered major industrial necessities as it applied mostly in parts production. Materials that commonly applied as cutting tool varied from polycrystalline diamond, cubic boron nitride, carbide, ceramic and cermet [1-3]. In machining process, there are many classes of the cutting tools according to the shape such as rectangular, square or round and cutting edge such as straight, bent, crank, radius or round [4-5]. The shape of the cutting tools were designed depended on the specific function, such as the materials that need to be cut and the process conditions [6].

Among various ceramic cutting tools that available in industry, alumina cutting tool (Al2O3) being among most frequently applied due to excellent hot hardness, high abrasive resistance and good chemical stability [7-9]. The properties of alumina based cutting tool depended on the characteristics of raw powders such as uniform grain structure, able to bind themselves naturally and able to growth in uniform grain size to avoid stress concentrations between the structure [10]. Nevertheless, the properties of alumina cutting tool also depended on the process parameters during powder compaction such as sintering temperature and pressing force to compact the insert [11-12]. All parameters interact each other to produce optimum cutting tool properties.

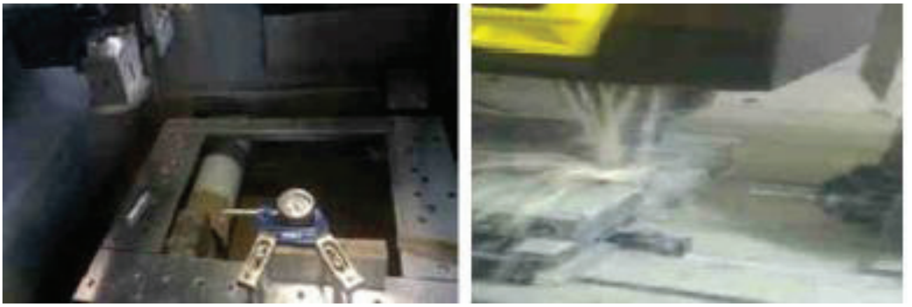
In the case of Malaysia industry, some machinist preferred to use carbide cutting tools due to availability in the market. However, some carbide cutting tool consumed high cost while their usage somehow not necessarily required especially for simple and short term machining operation. Most of the machining process using carbide cutting tool involving coolant to reduce the temperature inside machining [13-14]. In contrast, the alumina cutting tool can be obtained by fabricating the cutting tool themselves with simple manufacturing process. From raw powders, alumina can be compacted and sintered inside the furnace, similarly like other ceramic processing methods [15]. In addition, alumina based cutting tool specially applied for dry cutting. Such environment enable the usage of this cutting tool supports a healthy environment as no coolant required to run the operation [16].

In order to produce alumina powder based cutting tools, a special mould is required to compact to powders to form the green body. A simple mould should consist of core, cavity and injector. Core and cavity play important role to ensure that the mould capable to be inserted, pressed and compacted while the ejector functioned to press away the compacted powders out from the mould to form the green compact. The manual hydraulic press among the preferred technique due to low cost and easy handling procedure [17]. During compaction process, the alumina powders that inserted inside the mould will be directly press by the upper pressure for the hydraulic force. The small hydraulic press normally capable to be pressured up to 15 tons. However, if the mould applied at very high pressure, the mould body could be deformed and draw another problem such as misalignment between mould components. Misalignment between core, cavity and ejector would create troubles such as product stuck, distorted, tight and crash during part ejection process [18-19].

The objective of this study is to fabricate alumina based cutting tool by using powder processing, compaction and sintering process. Specific composition of alumina powders were directly pressed using hydraulic press in order to form the compacted inserts. Several pressure were varied in order to determine their effect on hardness and density. These samples then were sintered before machined with AISI 1045 to evaluate their wear performance. The assessment of the study also involves surface roughness evaluation and tool failure modes observation to assess the way of this cutting tools damage.

2.0 METHODOLOGY

A cylindrical bar of carbon steel with 36 mm diameter was prepared as the material for a mould development. To produce mold and core, CATIA V5 software is used to design and develop CNC programs for machining of carbon steel according to the designated shape. Meanwhile, EDM Wire Cut is used to make holes in the cavity according to the size of the cutting tool, taking into account the thermal decline after sintering. Figure 1 shows the EDM wire cut and CNC Milling operation to produce the mold.



(a) (b)

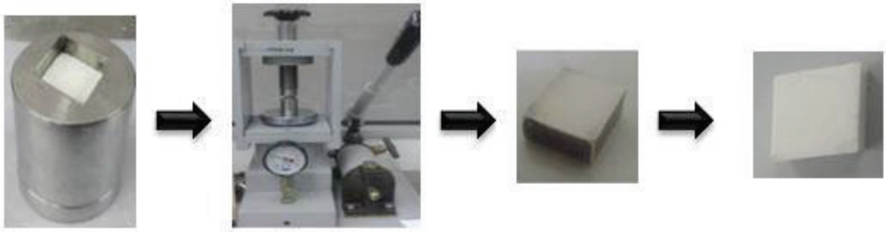
Figure 1: Mould machining process: (a) Wire cut machine and (b) CNC milling

It should be noted that the surface of these core, cavity and ejector section should be as fine as possible to facilitate smooth movement during product ejecting. This is to prevent sticking between core surface and ceramic powder which can resulting ceramic powder burst. Therefore, the surface of these parts was polished using sand paper to refine their surface finish quality. Figure 2 shows the comparison of part surfaces before and after polishing process.

(a) (b)

Figure 2: Mold comparison between (a) before polish and (b) after polish

100g alumina based powder was weighted and ball milled for 12 hours to ensure the segregation of the powder is homogeneous and to avoid any bigger size particles. The powder then inserted into the mould as shown in the Figure 3(a). The mould then undergone compaction using the manual hydraulic hand press machine under the pressures of 6, 7, 8 and 9 tons as shown in the Figure 3(b). Subsequently, the powder was ejected as a green body as shown in Figure 3(c). To obtain solid body, the green bodies were sintered at 1700oC in 4 hours soaking time as shown in Figure 3(d). To compare the hardness for each sample, HRA hardness tester was employed with for initial assessment for sintered sample. Density of the sintered bodies were measured using Density Tester, according to Archimedes Principle.



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

Figure 3: The compaction method procedures: (a) Powder pours into the mould, (b) The mould is pressed by hydraulic hand press, (c) The body is ejected out from the mould and (d) Ceramic cutting tool after sintering the white body colour

Machining trials were held using CNC lathe machine. The machining setup is shown in Figure 4. For each sample, constant cutting speed of 200 m/min, 0.05 mm/rev feed rate and 1 mm depth of cut were employed. AISI 1045 cylinder bars with the diameter of 50 mm and length of 150 mm were selected as a workpiece material. Machining time were recorded for each trial. At the end of machining process, the tool wear was measured using optical microscope, according to the ISO 3685 guideline. For surface roughness measurement, Mitutoyo Surftest SJ-410 Surface Roughness Tester was employed to evaluate the value of surface roughness.

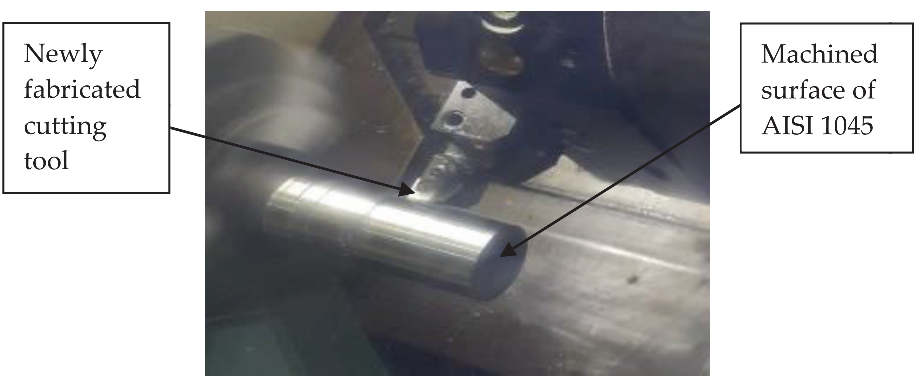


Figure 4: Alumina cutting tool on tool holder when machining AISI 1045

3.0 RESULTS AND DISCUSSION

Table 1 shows the value of density and hardness for each sintered ceramics cutting tool according to the pressure. It shows that the alumina based cutting tool successfully fabricated within the pressure from 6 to 9 tons. It should be noted that the mould unable to hold to pressure beyond 10 ton due to some component that stucked during compaction. The ejection process promoted partially crack to the alumina green body. During compaction process inside the mould, the pressure from the core delivered force to compress the alumina compact. If the load exceed beyond the limitation stress of the core, the excessive force could yield small deformation at the side of core, resulting minor contact between core and cavity. Such contact would lead to the friction, misalignment and minor distortions to the sliding core-cavity contacts. Such distortion would lead to the components stucked inside the mould.

Figure 5 shows the effect of pressure on density and hardness of sintered cutting tool in the form of graphs bars. The plot of both graphs show that value of density and hardness increased as the compacted pressure increased. During compaction process inside the mould, the pressure from the core resulting close powders packing between alumina particles. As alumina's particles became close each other, the air that trapped between particles and porosity can be reduced, resulting denser alumina compact. However, it should be noted that there were still micro-porosity appeared between the particles as a result of mismatch of size and shape between particles. Such micro porosity can be further reduced when the green compact sintered. During sintering process, the particles inside powder packing would expanded, towards the empty space between grain boundaries. Consequently, the air that trapped between particles would be released, reducing the pores inside the tool. As a result, the density of the ceramic body would be increased [20-23].

As the particles expanded during sintering, closer packing of alumina grains would allow dislocations between grain boundaries. As a result, the contacts between grain boundaries would interlocked each other thereby reducing dislocation mobility. Grain dislocations will block the deformation at the grain boundaries, resulting hardening to the structure which increased in the end increased its hardness [24].

Table 1: Density and hardness of sintered ceramic cutting tool according to the pressure

Pressure (Ton)	Density (g/cm^3)	Hardness (HRA)			
		1	2	3	Average
6	2.58	77.500	80.100	70.000	75.867
7	2.73	78.500	82.500	67.200	76.067
8	2.74	74.300	83.700	76.500	78.167
9	2.77	87.500	87.300	83.500	86.100

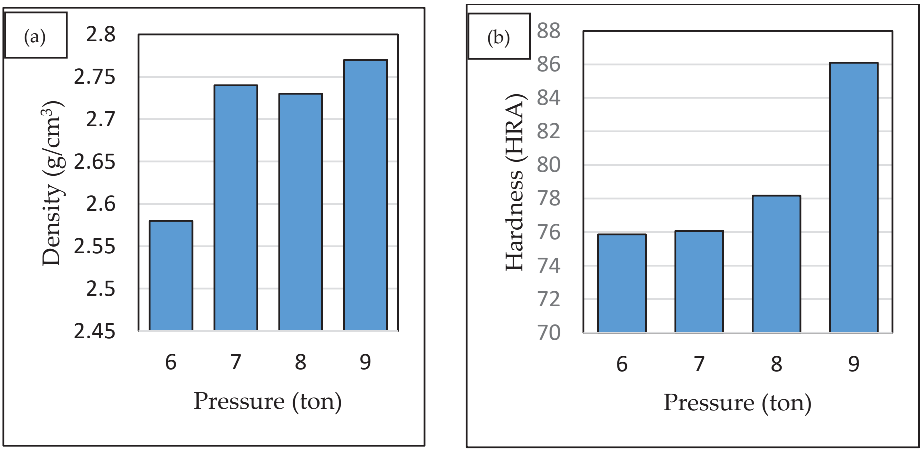


Figure 5: (a) Effect of hydraulic pressure (tons) on density (g/cm^3) and (b) Effect of hydraulic pressure (tons) on hardness (HRA)

Table 2 shows the results of wear rate for the alumina cutting tools that fabricated with different pressures when machined with AISI 1045. Figure 6 shows the effect of pressure on wear rate in the form of graphs bars. The lowest rate of wear rate of 0.0025 mm/s has been recorded by the cutting tools that pressured at 9 ton. While the highest wear rate of 0.0049 mm/s was recorded when the cutting tools that pressured at 6 ton applied. For cutting tools pressured at 7 and 8 tons, the wear rates recorded were 0.0031mm/s and 0.0028mm/s respectively. The overall trend bars show a decrease in wear rate when the compaction pressure increased.

Since the maximum compaction pressure produces higher density and hardness, it is expected that this cutting tool also consumed minimum wear rate. As the pressure increased, closer packing of alumina particles resulting strong attractive energy between particles, resulting better tribological resistance during materials sliding [25]. In addition, the expansion of alumina particles beyond the grains boundaries during sintering process resulting the distortions of crystal structure, producing numbers of dislocations and interlocking between particles. This resulting strengthening improvement of the sintered body [26-27].

Table 2: Wear rate for the alumina cutting tools that fabricated with different pressures when machined with AISI 1045

Pressure (Ton)	Cutting Time (Sec)	Wear on right side (mm)	Wear on left side (mm)	Average both side wear (mm)	Average wear rate (mm/s)
6	65	0.40	0.24	0.32	0.0049
7	76	0.18	0.29	0.24	0.0031
8	82	0.20	0.26	0.23	0.0028
9	111	0.24	0.32	0.28	0.0025

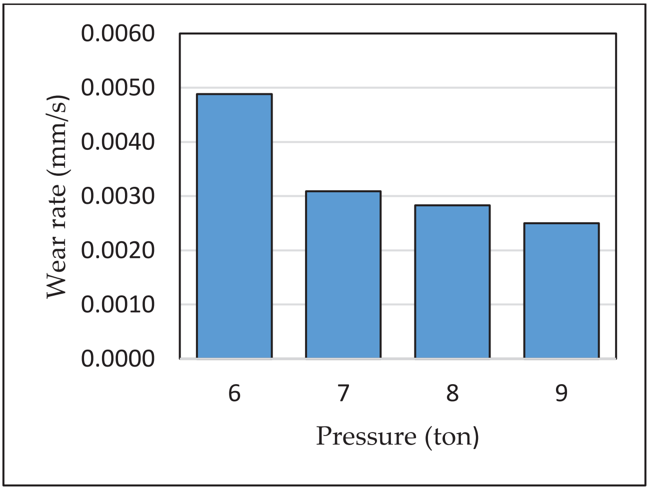


Figure 6: Effect of hydraulic pressure (tons) on wear rate (mm/s)

Figure 7 shows the microscopy presentation of the wear that occurred at the edge of cutting tool. Observation at the flank face of the cutting tools presented flank wears that concentrated at the small region of contact surfaces between the workpiece (Figure 7 (a-b)). Observation for the top surface of cutting tool demonstrated the edge crack at the tool tip and at the flank sides (Figure 7(c)). The analysis for the Figure 7 shows that the cutting tool easily to chip probably due to sharp edge of tool nose radius. The fact that sharp cutting edge invoked stress concentration at the tool tip. Since alumina cutting tool possess brittle characteristics, the load form the contact pressure focused on the small edge of tool tip resulting easy crack at the tool edge [28-29]. In addition, the machining was done in dry condition which generate localised heat as a result from the friction of tool and workpiece [16]. The presence of heat during machining would lead to the weakening edge of cutting tool, promoting crack to the tool, thus make it easier to wear along the cutting edge [30]. On top of that, heat generation can cause the material to melt and then cool rapidly as the surfaces exposed to the air. Such reciprocating heating and cooling at the contact interfaces could lead to the thermal fatigue that detrimental to the tool edge [31-32]. On top of that, heat generation can cause the material to melt and then cool rapidly as the surfaces exposed to the air. Such reciprocating heating and cooling at the contact interfaces could lead to the thermal fatigue that detrimental to the tool edge [33-34].

Table 3 shows the surface roughness recorded after machining AISI 1045 with fabricated cutting tool at different pressures. Figure 8 shows the surface roughness profiles printed from the surface roughness tester. The results show that the cutting tools that fabricated at pressure 7 ton gives the lowest value of Ra which is average at 1.24 µm. On the other hand, the cutting tool that fabricated with the pressure of 6 ton gave maximum Ra value of average 3.56 µm, reflected by its high wear rate. Meanwhile, the cutting tools that fabricated at pressure 8 and 9 tons gave close average Ra value of 1.89 µm and 1.84 µm respectively.

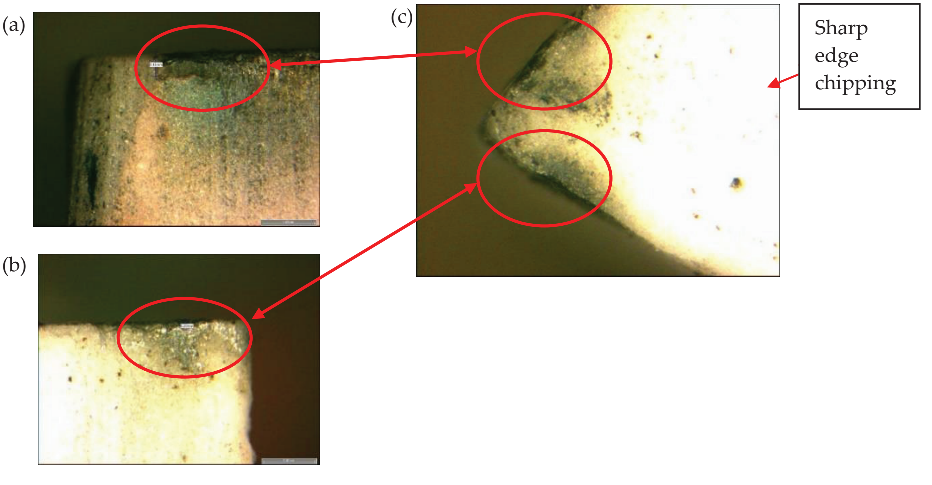


Figure 7: Wear at the edge of cutting tools: (a) Right flank side of tool, (b) Left flank side of tool and (c) Top side of tool

Table 3: Surface roughness value for each cutting tool

Pressure (Ton)	**Surface Roughness(μm)**				
	1	**2**	**3**	**4**	**Average**
6	3.79	3.63	3.53	3.27	3.56
7	1.06	1.69	1.03	1.17	1.24
8	1.91	1.85	1.90	1.89	1.89
9	1.93	1.82	1.74	1.88	1.84

There are many factors that controls the surface roughness of the machined surface. Clearly, combination of cutting parameters and tool nose radius play significant roles in influencing surface roughness [35]. The capability of tool nose radius to withstand longer cutting time before worn also critical issues to sustain fine average surface roughness [36]. In this study, the machining trial was performed around 2 minutes which considered very short. Even though the trials were conducted in a short time, the cutting tools already demonstrated significant wear and the minimum surface roughness already reach above 1 μm. The surface roughness also demonstrated fluctuated trend which reflected that wear formation not consistent for each cutting tool tested. The high value of the surface roughness means that the cutting tools incapable to cut the workpiece at its optimum.

Overall, this study demonstrates that alumina powder can be made as a cutting tool insert using simple compaction method and capable to machine AISI 1045 carbon steel. The newly fabricated alumina powder has adequate mechanical properties such as hardness and wear resistance to cut the steel without catastrophic failure, in which demonstrate promising results to be improved in the future. Improvement can be made with the suitable design of tool nose radius in which larger nose radius could be beneficial to reduce the stress concentrations [37]. In addition, the design of edge cutting tool with chamfer could be another possible alternative to increase the strength of cutting tool [38]. Nevertheless, the cutting tools can also be improved if proper processing parameters implemented and the usage of addition secondary phase such as zirconia, chromia, titanium carbide or silicon carbide [39-40].

4.0 CONCLUSION

Overall, this study demonstrates that alumina powder can be made as a cutting tool insert using simple compaction method and capable to machine AISI 1045 carbon steel. The newly fabricated alumina powder has adequate mechanical properties such as hardness and wear resistance to cut the steel without catastrophic failure, in which demonstrate promising results to be improved in the future. Based on the experimental finding the following conclusions can be drawn:

i. The density and hardness value of the cutting tool increased as the compacted pressure increased. Maximum density of 2.77 g/cm3 and hardness of 86.1 HRA achieved when the alumina powders compacted with 9 ton pressure.
ii. Wear rate of the fabricated alumina cutting tool decreased as the compacted pressure increased. Minimum wear rate of 0.0025 mm/s recorded when machining 9 ton pressurised alumina with AISI 1045. This correlated with the high hardness and density as the pressure increased.
iii. The fabricated alumina cutting tool experienced edge crack due to stress and thermal concentration at the sharp edge of cutting tool. This edge crack facilitated rough surface finish at the end of machining.

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