A Review on Alumina Based Ceramic Composites as Cutting and Machining Tool Materials

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ABSTRACT
New trends in the cutting and machining tool industry include faster cutting rate, dry cutting and highly wear resistant tool materials. These requirements are necessary for higher production rate and improved dimensional accuracy in the manufactured parts. With these challenges, ceramic composite cutting tools are now being utilized especially in the cutting and machining of hard and abrasive materials like superalloys and cobalt-based workpieces. In this paper, a review of the properties of cutting and machining tools, as well as some of the ceramic composite cutting tools being used today will be discussed.

Keywords: *Cutting and machining tools, alumina, silicon carbide, zirconia, titanium carbide*

INTRODUCTION
Cutting and machining are two important manufacturing processes for the production of dimensionally accurate parts. Almost, if not all, manufacturing companies employ these processes in every part of their production, whether it is in the front-line, in the end-line or in subsequent finishing operations. Thus, the performance of the cutting and machining tools significantly influence the productivity of every manufacturing industry. Various materials are being used as cutting and machining tools. These materials are available commercially, and are ranging from high-speed steels to carbides and diamonds, and now to ceramic composites. The continuous development of new tooling materials is done to accommodate every type of workpiece, even the hardest and most abrasive type like cobalt alloys.

According to Schneider Jr. 2006 [1], the machinability of the workpiece influences the cutting tool to be used. Thus, all types of tool, made from different materials, must be available to the machinist to be able to work on every type of workpiece material. He stated further that the best tool is not necessarily the most expensive or the cheapest one. The best tool is the one that can finish the job quickly, efficiently, and economically.

Generally, all cutting tools are hard and have high wear resistance. Unfortunately, no single material can machine all types of workpiece. However, the introduction of ceramic composites as new cutting materials brought significant increase in the cutting speed, as well as feed rate during machining operation. Now that the cutting technology is moving to dry cutting or without the use of coolants, ceramic is said to be a suitable candidate. But due to their brittle nature, additional processing should be performed, such as addition of reinforcements to increase toughness. This opened the opportunity for the development of ceramic matrix composites (CMCs) for the cutting and machining industry. Like other cutting and machining tool, the use of CMCs has limitations and no single CMC can be used in all types of materials.

In this paper, a review of the general properties of alumina-based ceramic matrix composite cutting tools as well as the fabrication method of the composite will be given.

PROPERTIES OF CUTTING AND MACHINING TOOLS

Due to the abrasive and high-stress conditions where the cutting tools are subjected, it is important that they have the required hardness, toughness, and wear resistance [1] in order to produce quality parts at a reasonable cost. The hardness and strength of the cutting tool must be maintained at high temperatures. This is termed as hot hardness. This is important because during machining operations, the temperature at the cutting edge could reach 1200 °C [2]. Therefore, the cutting material must not soften, or worse stuck to the workpiece during machining. The toughness of the cutting tool is also an important factor to consider. Tool fracture and chipping must also be prevented, especially during interrupted operations where the cutting tool might fail due to fatigue [1]. Further, it must also endure high cutting speed which is a necessary requirement for higher turn around rate in companies.

Aside from these, the cutting tool must have the necessary resistance to wear so that it will meet the expected tool life before it requires a replacement. The failure of ceramic composites due to wear is said to be a complex phenomenon [2, 3]. It is reported to be a combination of mechanical and chemical wear mechanisms. Mechanical wear can be attributed to the abrasion, plastic deformation, delamination, or a combination of these. It is found to be predominant at lower temperatures. Chemical wear, on the other hand, is due to diffusion and dissolution of the tool material into the workpiece. It is prevalent at high temperatures, high cutting speed, and dry cutting condition.

ALUMINA (Al_2O_3)-BASED CERAMIC CUTTING TOOLS

Because of their high hardness and good strength, as well as their good properties at elevated temperatures, ceramics are being developed as cutting tool materials. But due to their inert brittleness, reinforcements, normally in the form of whiskers, particulates and short fibers, are incorporated into the cutting tool to improve toughness, and consequently the tool performance. The reason for using these geometries is due to the easiness of fabrication. Discontinuous reinforcement ceramic composites can be process using conventional fabrication technique for monolithic ceramics such as slip casting or injection molding followed by sintering and hot pressing. In this section, emphasis will be given on alumina-based ceramic cutting tools.

Alumina is one of the most commonly used ceramics today. Its properties have already been studied extensively. Due to its desirable thermal properties, alumina is a suitable choice as a matrix for ceramic composite cutting tools. Alumina is commonly used as pipe work carrying solids suspended in gases or liquids, which requires good erosion resistance [4].

Silicon Carbide Whiskers (SICw)-reinforced

Among the discontinuous reinforcements for ceramic composites, SiC is by far the most popular. Its common trade names include Nicalon, Hi-Nicalon, SCS and others. As cutting tool reinforcements, SiC is typically in the form of whiskers due its high surface area. Normally, alumina will contain up to 25% SiC whiskers which tends to lie perpendicular to the pressing axis [4] during fabrication. SiC is less dense than alumina, therefore, increasing its concentration causes a decrease in the density of the composite cutting tool. This makes them lighter that usual. Addition of SiC also resulted to an increase in the value of the Young's modulus from 340(pure alumina) to 390 GPa for a composite with 25 wt. % SiC. Because of these factors, a significant increase in the specific modulus was observed in this composite type. Table 1 gives the properties of SiC_w/Al_2O_3 composite cutting tools.

Table 1. Properties of SiC_w/Al_2O_3 composite cutting tools [4]

% SiC	0	7	15	25
Density (Mg/m^3)	3.9	3.8	3.8	3.
Young's modulus (GPa)	340	340	350	390
Specific modulus [(Gpa)/(Mg/m^3)]	87	89	92	105
Bend strength (Mpa)	300	650	700	900
Weibull modulus	6	8	10	13
Fracture toughness (MPa $m^{1/2}$)	4.4	5.5	6.0	8.0
CTE x 10^6 (K^{-1})	8.0	8.0	7.0	6.0

As observed from the values given in Table 1, the incorporation of SiC in alumina enhances its fracture toughness, which is explained to be due to several toughening mechanisms like crack bridging, wake toughening, crack deflection, and pull-out. Further, when alumina is subjected to rapid fluctuating temperatures, it fails and fractures. However, the decrease in the coefficient of thermal expansion (CTE), increase in thermal conductivity and higher fracture toughness brought about by the addition of SiC resulted to better thermal shock resistance, as well as better erosion resistance.

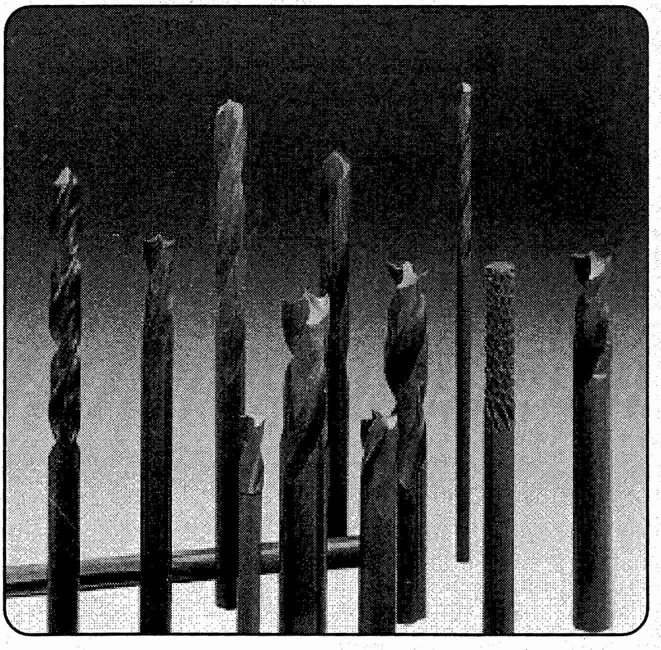

Figure 1. SiCw/Al_2O_3 Cutting Tools [5]

SiC_w/Al_2O_3 ceramic cutting tool is used for difficult to machine workpiece like Ni-based superalloys used in the gas turbine industry, Inconel, and other non-ferrous alloys. They are also utilized as cutting tool inserts for high-speed cutting of superalloys. In the cutting of Inconel 718, it shows three times better performance than the conventional ceramic cutting tool [7]. Figure 1 shows some examples of SiC_w/Al_2O_3 cutting tools. But its main drawback is that it cannot be used in cast iron and steel machining due to its dissolution in these materials. SiC was found to be chemically incompatible with iron [2]. Tools made from this composite have more predictable tool failure as compared to catastrophic failure in most ceramics. It also has longer tool life and lower maintenance cost. It produces parts with better surface finish at high cutting speed. Generally, this type of ceramic composite can be manufactured using the slurry method for monolithic ceramics. The schematic is shown in Figure 2.

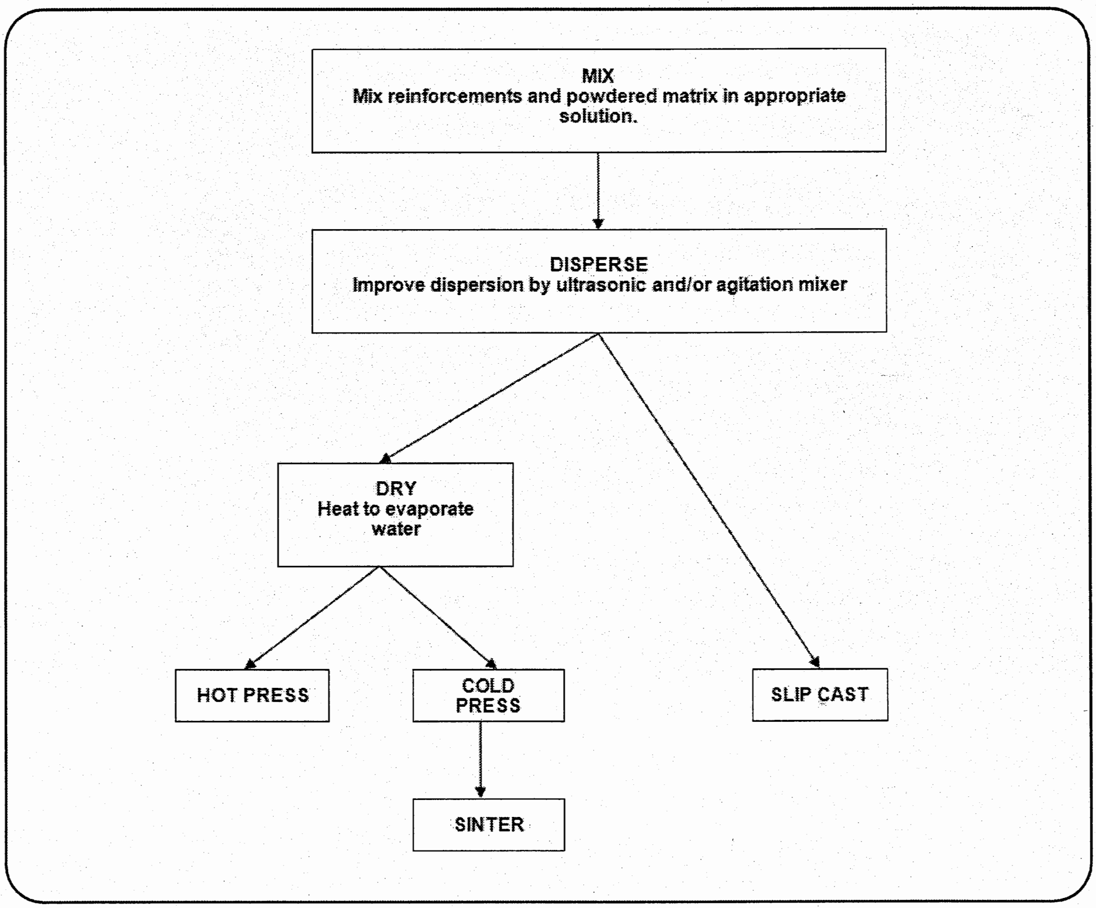

Figure 2. Simplified flow sheet for mixing as slurry before shaping for SiC_w/Al_2O_3 [4]

Zirconia Particulate (ZrO_{2p})-reinforced

Due to the problems in using SiC_w/Al_2O_3 as cutting and machining tool for hardened steel, new ceramic composite, like zirconia-reinforced alumina, is being developed. This will hopefully replaced carbide tools for machining and cutting steel. In using as reinforcement, zirconia is partially stabilized by the addition of dopants like yttria, ceria, and magnesia. Zirconia exists in three well-defined polymorphs [3]. One is the cubic form which is stable at temperatures above 2370 °C. Next is the tetragonal zirconia which exists between 2370-1150 °C, and lastly, the monoclinic zirconia, a low temperature polymorph (below 1150°).

Zirconia toughened alumina (ZTA) is strengthened by phase transformation and by precipitate or dispersion strengthening. This occurs when pure ZrO_2 is incorporated and dispersed in alumina, and is retained in its metastable tetragonal particles. These tetragonal particles are restricted by the rigid matrix due to alumina's low coefficient of thermal expansion. Thus they are constrained during the transformation to monoclinic structure. This transformation absorbs energy [3, 4]. And as a consequence, it generates toughness. This makes ZTA a good alternative to carbide tools for hardened steels. It was found that there is an increase in the cutting speed in using ZTA. Better surface finish in the workpiece is also produced. ZTA is fabricated using the conventional mixing and pressing for monolithic ceramics.

Titanium Carbide Particulate (TiC_p) -reinforced

The use of this ceramic composite is attractive due to its high thermal conductivity, thermal shock resistance and hot hardness. Even though this system is relatively new compared to those previously discussed, it is being utilized as an alternative to high-speed steels and carbides for the cutting and machining of cast iron, steel, stainless, and even refractory-Ni-based alloys. Its advantage lies on its compatibility with iron, which is the problem in SiC_w/Al_2O_3.

This composite has high transverse rupture strength and flexural strength. Its toughening mechanism is crack pinning. Crack propagating in the matrix is pinned by the reinforcements, and because of the additional energy needed in order to continue the dislocation movement, crack propagation is effectively stopped. Pinning of the stressed-induced dislocation motion causes dislocations bowing between and around the particles. This, then, generates dislocation loops around the particles. Another important toughening mechanism as reported by Gong and associates, 1991 [8] is the residual stress in the composite due to the mismatch in the properties of TiC and Al_2O_3.

Employing this cutting tool leads to high speed machining and lower cycle times. It also increases productivity, eliminates subsequent finishing operations, and consequently, lowers the production cost. Further, incorporation of this carbide in alumina led to an increase in the hardness at temperatures up to 800 °C [8]. Table 2 shows the comparison of the physical properties of oxide ceramics and TiC/ Al_2O_3 composite.

Titanium carbide reinforced alumina composite can be manufactured using the conventional technique for monolithic ceramic. However, self-propagating high temperature synthesis by hot pressing can also be used [3].

Table 2. Comparison of the Physical Properties of Oxide Ceramics and TiC_p/Al_2O_3 composite [8]

Cutting Materials	Oxide Ceramics $Al_2O_3 + ZrO_2$	TiC_p/ Al_2O_3 ceramic composite
Hardness (Vickers)	2000	2200
Modulus of Elasticity (kN/mm^2)	390	400
Bending Strength (N/mm^2)	350	600
Fracture Toughness ($mN.mm^2$)	4.5	5.4
Coefficient of Thermal Expansion (10^{-6} K^{-1})	7.5	7.0
Thermal Conductivity ($W\ m^{-2}\ K^{-1}$)	30	35

CONCLUSION

The use of ceramic composite cutting tools leads to improvement in the cutting speed, feed rate, productivity, and surface finish in manufacturing components. Though they have their limitations and drawbacks, they are still attractive alternative to the conventional cutting tool materials, especially when cutting very hard and abrasive workpieces.

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