Development and trend of ceramic cutting tools from the perspective of mechanical processing

Long Li and Yunfang Li*

School of Mechanical & Vehicle Engineering, Linyi University, Linyi, Shandong 276005, China
E-mail:liyunfang@lyu.edu.cn

Abstract. Ceramic cutting tools have attracted more and more attention because of their excellent machinability. This paper reviews the characteristics of alumina and silicon nitride that two kinds of ceramic cutting tools. The current development and application situations of these two kinds of ceramic tools are summarized, and we put forward the main development direction of ceramic cutting tools in the future.

1. Introduction

With the continuous development of processing technology in mechanical field, the demand on cutting quality is rising. The cutting tool performance is one of the decisive factors that affecting the machining surface quality, processing efficiency, processing cost and accuracy. High speed cutting technology is the most effective method to improve the processing efficiency. The traditional cutting tools, such as high-speed steel and hard alloy tools, are not capable of cutting engineering materials that with high speed, high strength, high hardness. However, ceramic materials mostly composed by ionic bonds (MgO, Al2O3), covalent bonds (BN, Si3N4) and mixed bond with ionic bond and covalent bond possess high melting point, high hardness, high chemical stability, oxidation resistance, high temperature resistance, corrosion resistance and other characteristics. Beside, ceramic material also has the advantages of low density, high elastic modulus, high strength and wear resistance, which makes its rapid development. At present, the most widely used in the field of high-speed cutting is alumina and silicon nitride ceramic cutting tools, because their good high-speed cutting performance greatly improve the production efficiency and product quality.

2. The performance of ceramic cutting tool

In recent years, more and more researchers paid attention to ceramic tool because of its high hardness, high strength, good heat resistance and chemical stability. The use of ceramic cutting tools can reduce the machining cost and improve the product quality and production efficiency.

2.1 High hardness and good wear resistance

The most notable feature of ceramic cutting tools is the high hardness and wear resistance. The hardness of silicon nitride ceramic tools is about 94HRC, which is far more than that of carbide cutting tools. The silicon nitride ceramic tools can process the high hardness materials which are difficult to be processed by the traditional cutting tools, and avoid the annealing process and save the resource. Under the same cutting conditions, the wear of silicon nitride ceramic cutting tool is only 1/15 of that of YT/15 carbide cutting tools that greatly improves the cutting ability of [1].

2.2 Excellent impact resistance
In addition to cut the high hardness materials with high-speed, ceramic tools can also do other processing with large impact, such as milling, interrupted cutting.

2.3 Good heat resistance and oxidation resistance in high temperature
In high temperature of 1350℃, ceramic cutting tool can still maintain a high degree of hardness and strength for continuous cutting. Therefore, the ceramic cutting tool can cut with a higher speed than that of hard alloy, and the cutting efficiency is 3-10 times higher than that of high-speed steel and carbide cutting tools, which greatly improve the production efficiency and effectively save resources. Experiment results show that Si3N4 has the best heat resistance in most ceramic materials.

2.4 Small friction coefficient with metal
Because of the low affinity with metals, the ceramic tool material is not easy to bond with the metals, and the cutting deformation is small. For example, compared with YTO5, the use of LT55 and SG4 ceramic cutting tool with a hardened 45 steel (HRC50-55) can make Fc decrease by 17.6%, Fp decrease by 14%, and Ff decrease by 28% [2]. In addition, under same conditions, the ceramic cutting tool can cut at higher speed and the roughness of the workpiece is lower.

2.5 High chemical stability
Even at a very high processing temperature, ceramic tools can still be continuously used for a long time.

2.6 Good thermal shock resistance
When the processing temperature changes rapidly, ceramic cutting tools possess a good ability to resist damage. For example, the thermal shock resistance of silicon nitride ceramic tool can reach up to about 700℃, which has obvious advantages compared with the traditional cutting tool material.

2.7 Low in cost
Al2O3 and SO2 are the main raw materials of ceramic cutting tool and very rich in nature resources. Compared with hard alloy, ceramic cutting tool greatly saves important metals (including W, Co, Nb, Ta), which significantly reduce the production cost to have a broad application prospect.

3. Types and applications of ceramic cutting tools
There are many kinds of ceramic tool materials, which can be divided into alumina and silicon nitride two categories according to their main components. Among them, 95% of the ceramic cutting tools belong to the alumina system, and the rest are mostly silicon nitride.

3.1 Alumina ceramic cutting tool
(1) Pure Al_2O_3 ceramics. The Al_2O_3 content of this kind of ceramic cutter reaches more than 99%, and by adding 0.1%-0.15% glass oxide (MgO, NiO, TiO_2, CrO_3), then to be made by cold pressing or hot pressing. The brittleness of this kind of cutting tool is very high that is easy to chipping.

(2) Al_2O_3-metal ceramics. Adding no more than 10% metal elements (Cr, Co, Mo, Fe, W, Ti) to Al_2O_3 can form metal ceramics. But this kind of cutting tools are not been widely used because of the low creep strength and poor oxidation resistance.

(3) Al_2O_3-carbide ceramics. Adding Mo_2C, WC, TiC, TaC, NbC, Cr_2O_3 and other carbides with certain percentage to Al_2O_3 can form Al_2O_3-carbide ceramics. This kind of ceramics has higher strength and hardness than pure Al_2O_3. In order to refine the grain and increase the density, this kinds of ceramic cutting tools are made by hot pressing process.

(4) Al_2O_3- carbide metal ceramics. Al_2O_3-carbide metal ceramics are made by hot pressing sintering, by adding Ni, W, Co, Mo and other metal elements to Al2O3-carbideceramics as binder. Because of the high strength of the connection, this kind of ceramic cutting tools has excellent cutting capability.

Alumina ceramic cutting tools are the most widely used ceramic tools in the world. The main component of alumina ceramic is Al_2O_3. Besides, it contains a small amount of SiO_2 ceramics and is known as high alumina ceramics. With the increase of alumina content, the performance of ceramic cutting tools is also improved. Alumina ceramic cutting tool has high temperature resistance, which can be used in the oxidation atmosphere to 1950℃. Therefore, the most suitable processing environment of alumina ceramic cutting tools is cutting hard and brittle metal materials with high speed, such as chilled cast iron or hardened steel, and copper alloy, graphite, engineering plastics and composite materials [3]. The processing speed of the cast iron is as high as 900m/min, and the cutting speed of the high temperature alloy is up to 120-240m/min [4]. Because the main ingredients of alumina ceramics is Al_2O_3 and Al_2O_3 has great affinity with aluminum, alumina ceramic cutting tool will severe wear when cutting aluminum and its alloy material. Therefore, alumina ceramic tools are not suitable for the processing of aluminum and aluminum alloy materials.

3.2 Silicon nitride ceramic cutting tool

(1) Single Si3N4 ceramic cutting tools. This kind of ceramic is produced by hot pressing and adding MgO additive, whose hardness is 91HRA-93HRA, bending strength is 0.7GPa-0.85GPa, the impact toughness is equivalent to YT30, the heat resistance can reach 1300-1400℃, and this materials has good oxidation resistance [5]. This kind of ceramics has small friction coefficient and strong adhesive ability, which is suitable for processing the material of casting silicon aluminum alloy and other material that prone to form chips.

(2) Composite Si3N4 ceramic cutting tools. They contain hard dispersed second phase heat resistant carbide or nitride, and possess high hardness, strength, fracture toughness and smaller thermal expansion coefficient. Composite Si3N4 ceramic cutting tools are more stable than the single Si3N4 ceramic cutting tools, and have stronger antioxidant ability. Therefore, this cutting tools is especially suitable for the rough and finishing processing, high speed cutting and heavy cutting of cast iron and high temperature alloy. The cutting durability is several times higher than that of the cemented carbide tool [6].

Silicon nitride is a kind of covalent bond which is composed of SiN4 tetrahedron. There are usually have two kinds of sintering processes, as shown in table 1. The strength, specific strength and specific modulus of silicon nitride ceramic tools are very high. The bending strength of Si3N4 at room temperature is 200MPa, which can be kept to 1200-1350℃. In hot pressed silicon nitride, the porosity is almost zero, the bending strength at room temperature can reach up to 800-1000 MPa, the specific modulus is 11.9×104 MPa, which is more than 4 times to that of steel.

Table 1. Sintering process and characteristics of silicon nitride

Sintering process	Advantage	Disdvantage
Reactive sintering (Nitridation of Si powder at high temperature)	Almost no shrinkage during sintering, and complex shapes can be obtained	Low density, low strength, and poor corrosion resistance
Hot pressing sintering (Uniaxial compression and sintering simultaneously)	With fewer additives can be densified, and possess high strength, corrosion resistance	Only can make simple shapes, and sintering additives reduce high temperature strength

3..3 Application of ceramic cutting tools

Some text. At present, the usage of the ceramic cutting from advanced industrial countries represented by Germany and Japan accounts for 5%-10%, and showed a increasing trend year by year [7]. In the processing of the casting process in Germany, 70% is completed by ceramic tools. Kyon2000 type Si3N4 matrix ceramic tool of Kennametal company in the United States, metal removal rate is 7 times than that of coating hard alloy in cutting nickel based superalloy with high speed, which can process

cast iron and high temperature alloy with large feed rate and cutting speed.

The development of the application of ceramic tools is rapid in our country. The annual output of ceramic tools has reached 760 thousand in 1998, and the study on ceramic cutting tools have also been squeezed into the international advanced ranks. But the application of ceramic tools have not been improved. As early as 1970s, Tsinghua University has successfully developed a Si3N4 ceramic tool. And was first realized in the world that using hot pressed Si3N4 ceramic cutting tool to perform a variety of processes (lathe, milling, thread turning, screw rod, etc.) for a variety of difficult machining materials (hardened steel, chilled cast iron, hot graphite, glass steel), which has aroused the attention and interest of domestic and foreign academic filed [8]. Today, the domestic scientific researchers have developed theFT-80, ST-4 and other models of ceramic cutting tool materials with excellent performance. Ceramic tools in our country are currently used in semi finish and finish machining for lathe, boring, end milling and planing, and rough machining for steel and iron castings with relatively uniform margin.

4. Prospect of ceramic cutting tools

Although studies have shown that the performance of ceramic materials is excellent, they also have some shortcomings. Especially the low toughness and high brittleness of ceramics that seriously restrict the development of ceramic cutting tools. However, with the continuous innovation on ceramic cutting tool technology in recent years, the variety of ceramic cutting tool has been fully developed, and a number of new ceramic cutting tools will play a key role in machining field in the future.

4.1 Coated ceramic tools

Cutting tool coating technology is a hotspot in recent years, in which the ceramic tools with good toughness are coating treated by hot pressing, CVD, PVD or sol-gel process. The TiN/TiAN coating combines the advantages of both TiN and TiAN, which is very suitable for high speed and dry cutting. Compared with uncoated ceramic cutting tools, they have better abrasion resistance and longer service life, can withstand relatively large cutting to obtain high surface quality.

4.2 Ti (C, N) - based cermet cutting tools

Ti (C, N)-based cermets are a new kind of particle reinforced composites developed on the basis of TiC-based cermets in early 1970s. It is a new kind of materials, in which using TiC, TiN or Ti (C, N) powder as a hard phase, adding WC, TaC, VC and other refractory metal carbide, using Ni-Mo (or Mo2 C) as binder, and sometimes instead some Ni with Co [9]. Cutting tools made by this materials can be used for machining brittle steel, alloy steel, cast iron, glass fiber and other non-metallic materials, and finishing machining steel and cast iron with the cutting speed of 300-500m/min.

4.3 Whisker reinforced ceramic cutting tools

Whisker reinforced ceramic composites can improve the toughness and strength of ceramic composite materials. Adding appropriate amount of whisker with few defects can effectively improve the fracture toughness of tool materials, in which the effect of whisker reinforcement is achieved by phase transformation. According to the previous study, when the volume fraction of the whisker content is between 15%-30%, the load can be effectively transferred from the substrate to the whisker. Whisker reinforced ceramic cutting tool is a special kind of cutting tool. It possesses good impact toughness resistance and thermal shock resistance, that can be used to machine hardened steel (up to HRC65) and medium hardness steel with high speed, and cut in cutting fluid conditions that is not present in other ceramic tools [10, 11].

4.4 Functionally gradient ceramic tools

The functionally gradient ceramic tools are prepared by vacuum sintering and surface nitriding treatment. Because the composition distribution changes according to a certain gradient, the damage resistance in the high speed cutting is obviously improved compared with the common ceramic cutting

tool [12]. The service life of the gradient ceramic tool is about 1-2 times of the cemented carbide YS10 tool, and the higher the cutting speed is, the more obvious of the superiority of the gradient ceramic tools.

4.5 Rare earth element modified ceramic cutting tools

Rare earth elements can purify the interface, reduce pores and improve the bonding strength and toughness of interface. At present, the rare earth elements in Ti (C, N)-based cermets are mainly Y, Er and La. Rare earth elements are generally added to Ni powder in the form of intermediate alloy, and used as binder to exhibit a better effect [13].

5. Conclusion

Ceramic cutting tools are the most promising cutting materials in twenty-first Century. Because of the advantages of high melting point, high hardness, high chemical stability, high oxidation resistance, high temperature resistance, corrosion resistance, ceramic cutting tools not only improves the production efficiency, reduces the processing cost, but also makes the green processing become a reality. With the rapid development of science and technology, the kind of ceramic cutting tools of China is increasing and the performance is constantly improving. Ceramic cutting tools as ideal high speed cutting tools will play great potential and be used more and more widely in the near future.

References

[1] S. Yan, S. Chen, B.Q. Zhang, Application and development of the ceramic cutting tools, Manufacturing Technology & Machine Tool 0 (2011) 53-55.
[2] D.C. Gong, Discussion on performance and application of ceramic tool materials, Guide of Sci-Tech Magazine 0 (2012) 232-232.
[3] P .Wen, Development trend of new ceramic tool materials, Foshan Ceramics 14 (2004) 36-37.
[4] X.T. Bo, NC tool material adapting with high-speed cutting, Heat Treatment 30 (2015) 48-48.
[5] B. Zhou, Development and application of silicon nitride ceramic cutter, Shanxi Science and Technology 0 (2004) 67-68.
[6] H. Zhang, New types of ceramic cutting tools and its development prospect, Mechanical Research & Application 19 (2006) 1-3.
[7] X. Ai, J.X.Deng, J. Zhao, C.Z. Huang, Z.Q. Liu, Development and application of ceramic cutting tools, Machinists (Metal Cutting) 0 (2000) 4-6.
[8] M. Li, C.Z. Huang, L. He, J. Sun, H.L. Liu, A status quo on silicon nitride matrix ceramic tool material, Journal of Ceramics, 24 (2003) 58-62.
[9] W.H. Wu, Y.X. Li, P.K. Bai, W.P. Wu, Research progress of Ti(C,N)-based cermets composite, Hot Working Technology 45 (2016) 12-14.
[10] M.Z Gao, S.R. Xiao, X.C. Deng, New ceramic tool of research and application, Coal Mine Machinery 29 (2008) 83-85.
[11] C.Y. Xia, Ceramic material and application of high-speed machine, Coal Technology 25 (2006) 8-10.
[12] S .W. Tang, D.S. Liu, P.N. Li, W.B. Tang, D. Tang, Preparation and cutting performance of Ti CN-based functionally gradient cermets, Journal of Functional Materials 13 (2014) 13126-13130.
[13] S.C . Zhao, Factors influencing mechanical properties of Ti (C, N)-based cermet, Heat Treatment 31 (2016) 1-7.