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Development of new ceramic cutting tools with alumina coated carbide powders

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Abstract

An experimental investigation is carried out to coat two types of carbide powders, TiC and (W, Ti)C, with an alumina ceramic using a sol-gel technology. The coated carbide powders are then fabricated into two kinds of new ceramic tool materials by the hot pressing method. A scanning electron microscope (SEM) observation reveals that in general the matrix (carbide) grains are uniformly coated with the alumina ceramic and the microstructure of the new tool materials is more homogeneous than that of conventionally made ceramics. The tests of mechanical properties and wear resistance in machining are finally conducted. It is shown that when machining a mild carbon steel the new tool materials can increase the tool-life by up to 100% as compared to other two ceramic tool materials that have the same matrix but fabricated in the conventional way, while the fracture toughness is improved by up to 33%. When compared with a hard coated carbide tool, the new materials exhibit a superior ability in maintaining the wear resistance during the entire tool-life.

Keywords: Powder coating method; Sol-gel technology; Coating; Ceramic tool; Tool wear

1. Introduction

Machining is a major manufacturing process and plays a key role in the creation of wealth. The need for improving the technological performance of machining operations as assessed by tool-life, forces, power and surface finish has long been recognized to increase the economic performance of the machining operations. Continual improvements in the technological performance of machining operations have been sought through research and development including new and more wear resistant tool materials as well as new geometrical tool designs. One of the important development in the past decades has been the advanced ceramic tool materials that are being increasingly used in machining operations. While ceramic tool materials can significantly increase the tool-life and hence reduce the production times and costs, the extremely low fracture toughness associated with these materials has limited their applications, particularly in the intermittent or discontinuous cutting processes such as milling [1]. In the traditional ceramic fabrication process, the alumina matrix is mixed with additives such as carbides, the mixture is then hot-pressed to form ceramics. Based on this process, to increase the toughness will require the change in the proportion of alumina and additives, which will normally compromise the hardness and wear resistance of the tool materials. Hard surface coating on high toughness materials, such as high speed steels and carbides, has been a major tool improvement in recent years, whereby the cutting tools have good wear resistance while maintaining good toughness. Hard coatings such as TiN, TiC and Al_2O_3 have been used

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and claimed to improve significantly the tool-life, enabling components to be machined at higher ‘economic’ speeds, and reduce the forces and power due to the lower frictional coefficients on the rake face [2, 3]. However, the thin layer hard coatings do not have good sustainability once the tool wear occurs.

The present work attempts to study the possibility of coating the carbide grains or powders with an alumina ceramic, from which the tool inserts are made, to maintain the effectiveness of the coatings in improving the cutting performance. It is expected that the coatings will prevent the matrix (carbide powder) from growing during the fabrication (hot pressing) process, and the tool material fabricated from the coated powders will result in more homogeneous microstructure than that fabricated by mixing the alumina and carbide. The mechanical properties of the materials can be further improved by the synergism of different material phases contained in the coating. Consequently, the new approach shall produce a tool material with improved hardness and fracture toughness. For this purpose, a sol-gel method [4] is used to coat two kinds of carbide powders, TiC and (W, Ti)C, with an alumina ceramic. Two types of ceramic tool materials, named as FTC1 and FTC2, are then fabricated respectively from the two ceramic-coated carbide powders by the hot pressing technology. A scanning electron microscope (SEM) analysis is carried out to observe the morphology of the fractured surfaces and to study the coatings and microstructure of the new ceramic tool materials. Finally, the tests of mechanical properties and the cutting performance of the new ceramics are presented.

2. Powder coating technology and tool material fabrication

Based on the size of the substrate (or matrix) being coated, there are two types of coatings, particle coating and powder coating. The former refers to coating on large particles of several millimeter in diameter (such as pills and plant seeds etc.) and, therefore, it is also called composite particle coating [5], and the latter refers to coating on grains that are less than one micrometer in diameter. To uniformly coat powder grains has proven to be very difficult. Attempts have been made by researchers to develop coating technologies for powder grains. Particular attentions have been paid to the sol-gel technology which was originated by Jebelmen in 1846 [4] for material preparation. During the past decades, the sol-gel technology has been developed as the most promising method for material fabrication. It is claimed by Ding [6] that the current sol-gel technology has a number of advantages over the other methods, namely it requires low fabricating temperature, and produces more homogeneous organisation and higher material purity with easy-to-control reaction process. An early study in applying the sol-gel technology has found that the silicon carbide whiskers coated with a thin alumina layer of 2-10 nanometer are characterised by high oxidation resistance [7]. There is a strong bonding interface between the coating and the substrate. The coated silicon carbide whiskers can be uniformly dispersed and distributed to whisker reinforced alumina ceramic tool material without aggregates and result in high mechanical properties, especially the interfacial bonding strength. Warrier [8] has also shown that mullite ($3Al_2O_3{\cdot}2SiO_2$) can be successfully coated on silicon carbide particle by the sol-gel method with improved carbide surface integrity. Consequently, the sol-gel technology will be used in the present study to coat an alumina ceramic on two types of carbide powders before they are fabricated into ceramic tool materials.

2.1 Preparation of alumina sol

The mechanical properties of the ceramic tool material fabricated from coated carbide powders depend heavily on the sol quality. In general, an alumina sol characterised by fine grains, a homogeneous organisation, an appropriate flowing deformation and a suitable cross linking is preferred. A trial and errors experimental approach based on past experience in ceramic research has been used to arrive at the best possible sol which is then used for coating the carbides. It has been found that an alumina sol with the concentration of 0.5~0.6 mol/L gives the best coating result in the present study.

The process in fabricating the two types of ceramic tool materials from the coated carbide powders is shown in Fig. 1. The materials used for making the sol or boehmite solution were 99.9% purity aluminium-iso-propoxide ($Al(C_3H_7O)_3$) (as precursor), distilled water (as solvent) and 65% nitric acid solution (as catalyst). The aluminium-iso-propoxide contains 24.8% of alumina (Al_2O_3) in terms of mass. During the process, the aluminium-iso-propoxide was diluted with distilled water and hydrolysed by water bath heating at 85-95°C for 0.5 hour with the assistance of mechanical stirring to increase the hydrolysing rate. A condenser was used to prevent useful compositions in the mixture from vapouring during the heating process. A suitable amount of the nitric acid solution was then added into the diluted solution so that the final solution contained about 12% to 16% of HNO_3. This solution was then stirred for 24-48 hours at the temperature of 85-95° C to arrive at a stable and transparent alumina sol.

2.2 Fabrication of ceramic tool materials

The matrix materials coated were TiC and (W, Ti)C powders with a grain size of 0.5-1.0 um. For a good coating result, the carbide powders should have clean grains without aggregation. The carbide powders were first cleaned and dispersed by an ultrasonic generator before added into the alumina sol.

It has been found that too low a concentration of alumina sol resulted in too thin coating on the powder; inversely, too high a sol concentration resulted in powder aggregation. The best coating thickness was determined by experiments to arrive at the stage where the maximum thickness was achieved without powder aggregation. It has been found that an alumina sol concentration of 0.5-0.6 mol/L is appreciate for coating the carbide powders TiC and (W, Ti)C to the best coating thickness.

The carbide powders should be uniformly coated with the alumina sol once they were fully mixed with the sol and dispersed. The coated carbide powder solution was then deposited, filtrated, heated and dried in a vacuum chamber, mechanically crushed to separate the powders and screened to eliminate aggregated powders.

The coated carbide powders were finally mixed with additives, which were 3~4% Mo, 3~4% Ni, 2~3% MgO and 2~3% CaO in terms of mass, and hot-pressed at the temperature of 1750-1800°C for 40-50 minutes in a graphite die with a 30 MPa pressure. The hot pressing process converted the alumina sol on the surface of the powders into the required alumina ceramic.

Consequently, two new cutting tool materials, which are named FTC1 and FTC2 ceramics made respectively from TiC and (W, Ti)C carbide powders, have been achieved. A further study is required to analyse the mechanical properties and cutting performance (wear resistance) of the new tool materials.

3. Microstructure and mechanical properties of the new ceramic tool materials

3.1 Microstructure

Artificially made fractured surfaces of FTC1 and FTC2 were observed under a scanning electron microscope (SEM) and some selected and representative photomicrographs are given in Fig. 2. For a comparison purpose, the photomicrograph of a commercially available ceramic tool SG4 [9] containing 55% alumina and 45% (W, Ti)C carbide is also given in the figure.

It can be seen from Figs. 2(a) and (b) that there is a layer of alumina (white areas) on the matrix grains. The alumina layer for the FTC1 and FTC2 ceramics is much more uniform than the SG4 ceramic made by the conventional direct mixing methods shown in Fig. 2(c). The microstructure for the new ceramics is clearly more homogeneous than that of the SG4 ceramic. The uniform coatings will not only stop the grains from growing during the fabrication process, hence maintaining the hardness of the grains, but also increase the hardness of the grain surfaces. Nevertheless, some voids (or air cavities) along the grain boundaries and grain aggregations due to ineffective dispersion can be observed for the new ceramics, as indicated by the arrowheads in Figs. 2(a) and (b). Thus, there is still a considerable scope to optimize the fabrication process and further improve the mechanical properties of the ceramics. It is also noticed that the fractured surfaces of the new materials have grey areas and sliding tracks, as shown in the figure. The former implies the breakage along the grain boundaries during fracturing, while the latter indicates cross-sectional grain breaking due to the good bonding condition. The cross-sectional breakage of the high strength matrix grains requires more fracture energy and has lower crack propagation rate, which in turn increase the flexural strength and fracture toughness.

3.2 Mechanical properties

The flexural strength, hardness and fracture toughness of the new ceramics were tested and compared with other tool materials while the wear resistance was assessed by cutting tests which will be presented later in the paper. The flexural strength was measured in static air using 3x4x30 mm polished test bars under three-point bending with a span of 30 mm and a loading rate of 0.5 mm/min with an electronic universal test machine WD-10. The test specimens were made using the same materials and process as the tool inserts.

The fracture toughness was obtained from the materials hardness value measured with an indentation method. This approach is simpler than the other fracture toughness measuring methods, such as the four-point bending method, while fracture toughness values obtained are essentially the same as those from the direct test method [10]. The indenter is the Vickers DPH type and the applied static load is 196 N. In the tests, 10 samples were used, 10 indentations were made on each sample, and 4 crack lengths were obtained from each indentation. For each test, the fracture toughness value was evaluated by using Eq. (1) found in [11]:

$$K_{IC} = 1.99 \cdot \left(\frac{c}{a}\right)^{-1.5} \cdot \left(\frac{a}{1000}\right)^{0.5} \cdot HV \qquad (1)$$

where K_{IC} is the fracture toughness(MPa.m$^{0.5}$), a is a half of the indentation diagonal length(mm), c is a half of the crack length (mm) and HV is the Vickers hardness (N/mm^2).

Thus, a total of 400 fracture toughness values for each ceramic were obtained and the average was taken as the final fracture toughness value.

The hardness was measured with Vickers hardness test. A diamond indenter was used with a total load of 196 N. The hardness for each composite was the average of the 10 samples with 8 indentations on each sample.

These mechanical properties for the new ceramic tools (FTC1 and FTC2) are given in Table 1. For a comparison purpose, the properties obtained under the same test conditions for other two commercially available ceramic tool materials, LT55 and SG4 [9], are also given. The reason for choosing these two ceramics is that LT55 and SG4 are also made from TiC and (W, Ti)C, respectively, i.e. the LT55 ceramic contains 45% alumina and 55% TiC carbide, and the SG4 contains 55% alumina and 45% (W, Ti)C carbide as mentioned earlier. Comparing the FTC1 material with its counterpart LT55 reveals that the new material has increased all the three mechanical properties (flexural strength, hardness and fracture toughness) by 10.7%, 6.8% and 33.3% respectively. The corresponding percentage increases of the FTC2 tool with respect to the SG4 ceramic are 22.5%, 3.9% and 10.9%. As mentioned above, the coated matrix grains do not grow in the fabrication process and the materials fabricated from the coated powders tend to have a more homogeneous microstructure. In addition, the coating on particles can improve the bonding condition compared to the conventional ceramic fabrication process using carbide powders. These are believed to be the reasons in improving the mechanical properties.

Some properties of a coated carbide tool YB01 is also given in Table 1. YB01 is a grade P10 carbide with totally 7 μm double TiC and Al_2O_3 coatings and is an earlier version of the YB215 coated carbide tool manufactured by Zhuzhou Carbide Works in China. The substrate of this tool contains TiC (the same as the matrix for the FTC1 ceramic) while the coating is Al_2O_3 (the same as the powder coating material for the two new ceramics). It was believed to be reasonable to use this coated carbide tool for comparison. As expected, the FTC1 and FTC2 ceramics have a lower flexural strength (by 28% and 14% respectively) than the P10 grade carbide (the substrate of YB01), but an increased hardness (by more than 40%) as compared to the substrate of the carbide tool. However the hardness of the coatings on YB01 is about 20% high than the new ceramics. Further machining tests are required to examine the wear resistance for the ceramics as well as the coated carbide.

4. Wear resistance in machining

The wear resistance was assessed by cutting tests turning two carbon steels on a 7.5KW, 400 mm lathe (model CA6140). The two workpiece materials were a 0.45%C mild carbon steel (#45 steel) and a 1.0%C carbon tool steel (T10A steel) bar with a hardness of 25 HRC and 58 HRC, respectively. Four types of ceramic inserts, FTC1, FTC2, LT55 and SG4, and one type of coated carbide YB01 inserts were used in order to assess and compare the wear resistance of the tool materials. All the lathe tools were prepared to have an identical geometry, i.e. normal rake angle γ_n=-5°, normal clearance angle α_n=5°, major cutting edge inclination angle λ_s=-5°, major cutting edge angle K_r=75°, and the nose radius r_ε=0.2 mm. It should be noted that although large normal rake angles can be used for the carbide tools, the angle selected was to coincide with the ceramic tool. In addition, all tools have a chamfered edge of 0.2 mm long with a -15° normal rake. All the tools used had no chip breakers and no coolant was used for all the cutting tests.

When cutting the 0.45%C carbon steel, a cutting speed of 160 m/min, a feed rate of 0.2 mm/rev. and a depth of cut of 0.3 mm were used. Likewise, the cutting conditions used for the 1.0%C tool steel were the cutting speed = 182 m/min, feed rate = 0.1 mm/rev. and the depth of cut = 0.15 mm. The reduction of the feed and depth of cut for the latter material was made taking into account its difficult-to-cut nature and the machine tool technological limits. During the course of the cutting tests, the tool wear (wearland) was checked frequently with a tool maker's microscope. Three inserts for each tool material were used for each workpiece material with their wearland measured at the same cutting time intervals. The average readings were then taken and plotted in Figs. 3 and 4. It is shown by the figures that the wearland growth for the five tool materials follow the common patterns whereby a rapid increase is noticed at the initial cutting stage due to the asperity of the tool surface, followed by a nearly steady increase with the actual cutting time.

4.1 Machining of the 0.45%C carbon steel (#45 steel)

As shown in Fig. 3, when machining the 0.45%C carbon steel, the wear resistance of FTC1 and FTC2 has been found to be markedly stronger than that of the LT55 ceramic. It can thus be deduced that the ceramic-coated powders for the FTC1 and FTC2 ceramics play an effective role in increasing the wear resistance under the test conditions. If using an ISO recommended 0.3 mm wearland size as the tool-life criterion, the LT55 ceramic can have a tool-life of about 11 minutes while those for the two new ceramics will be over 22 minutes with more than 100% improvement.

When compared with the coated carbide tools (YB01), the new FTC1 and FTC2 ceramic tools again showed stronger wear resistance. It is noted that the coated carbide tools showed a comparable trend with the FTC1 ceramic within the first 11 minutes of cutting. The latter then demonstrated its superiority in the subsequent cutting. This trend proves that the coating on the carbide gradually lost its effectiveness while the tools made from coated powders possessed consistent wear resistance during the entire course of cutting. If a 0.3 mm of wearland size is again used as the tool-life criterion, the FTC1 ceramic can increase the tool-life by about 23% as compared to coated carbide. From the tool wear curves, a further increase can be anticipated if a large wearland size is employed as the tool-life criterion for rough machining.

The FTC2 ceramic tool shows a similar trend as compared to the FTC1 tool at the stable cutting stage. It is in turn shows a great advantage in wear resistance over the coated carbide tool (YB01) in a similar fashion to the FTC1 tool, but at an increased scale due to the initial wear effect most likely as a result of the asperities on the tool surface. Thus, FTC1 and FTC2 are the new alternative tool materials for cutting 0.45%C or similar carbon steels.

4.2 Machining of the 1.0%C tool steel (T10A steel)

As shown in Fig. 4, the initial wear rate for the FTC2 tool is greater than those of the other three materials but is then reduced after about 2.5 minutes of cutting. It is believed that the surface of the tool was not well prepared, which contributed to this rapid tool wear. Nevertheless, the final tool-life at 0.3 mm of wearland is only marginally shorter than the SG4 ceramic tool. In the stable wear region, the wear rates for FTC1, FTC2 and SG4 are comparable. The overall wear for the FTC1 tool is constantly lower than that of the SG4 ceramic tool, indicating an improved wear resistance by the particle coating.

Although the graphs show that the FTC2 tool is associated with an overall larger wearland size than the FTC1 tool, it is again the result of the initial rapid wear occurred on the FTC2 tool. The wear rates for the two new tools after about 4 minutes of cutting show an identical pattern, as is the case in Fig. 3. Based on the current cutting tests, the two matrix materials, TiC and (W, Ti)C, from which the two new tool materials were made did not show any markedly difference in affecting the wear resistance.

While the YB01 surface coated carbide inserts show some superiority over the new FTC2 tool and has no significant disadvantage as compared to the new FTC1 tool at the initial cutting stage, the two new tool materials have soon demonstrated their advantage in wear resistance over the coated carbide tool (after about 5 minutes for FTC1 and about 8 minutes for the FTC2 tool). Using a 0.3 mm wearland as the tool-life criterion, the new tool materials can increase the tool-life by more than 50% over the coated carbide tool. This again proves that the coating on the particles has played an important role in improving and maintaining the wear resistance, and the new tool materials may be used as an alternative for the popularly used hard coated carbide tools.

5. Conclusions

A sol-gel method has been used to coat two types of carbide powders, TiC and (W, Ti)C, with an alumina ceramic, and two kinds of new ceramic tool materials have been successfully developed with the coated carbide powders. A SEM observation on the fractured surfaces of the new tool materials has shown that each carbide grain has been uniformly coated with a layer of alumina and the new materials have a more homogeneous microstructure than those fabricated using the conventional method. The material tests have found that the mechanical properties of new tool materials have been considerably improved as compared to other ceramic tool materials, where the fracture toughness has been increased by up to 33%. The machining tests have shown that the new materials have a superior wear resistance over the other ceramics in the normal wear stage, and can maintain a good wear resistance over the entire tool life.

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Table 1. Mechanical properties of various tool materials.

Mechanical Properties	FTC1	LT55	FTC2	SG4	YB01
Flexural Strength σ_{bb} (MPa)	830	750	980	800	1150
Hardness HV (kg/mm^2)	2350	2200	2390	2300	1650*
Fracture Toughness K_{IC} (MPa.mm$^{0.5}$)	5.6	4.2	5.1	4.6	-

* The hardness of the coating is 3000 kg/mm^2.

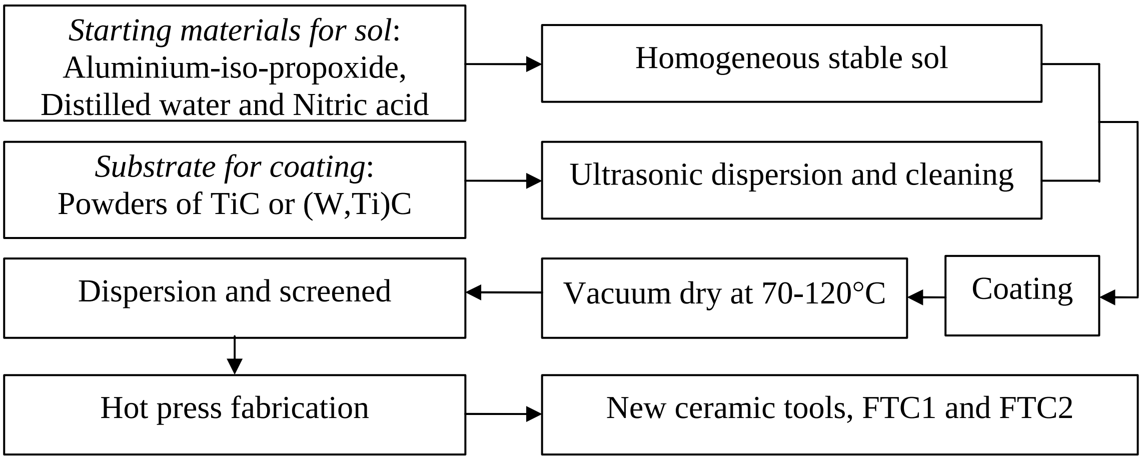

Fig. 1. Fabrication process of the new ceramic cutting tools.

e-copy for Figs. 2 (a), (b) and (c) are not available

Fig. 2. Fractured surface morphology of the FTC1, FTC2 and SG4 ceramics.

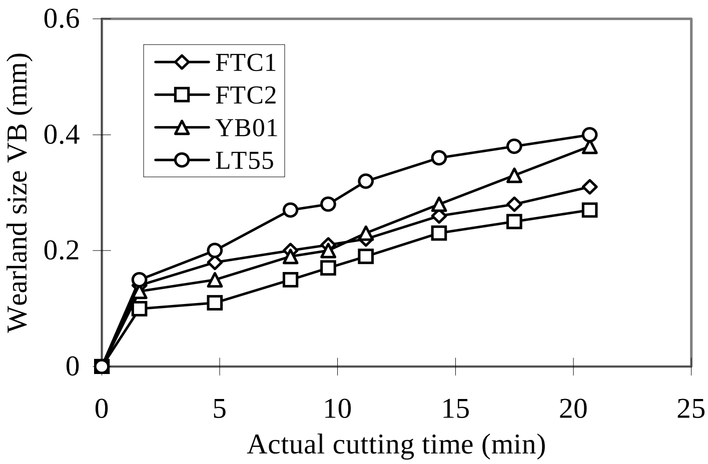

Fig. 3. Tool wear vs. actual cutting time in machining #45 steel.

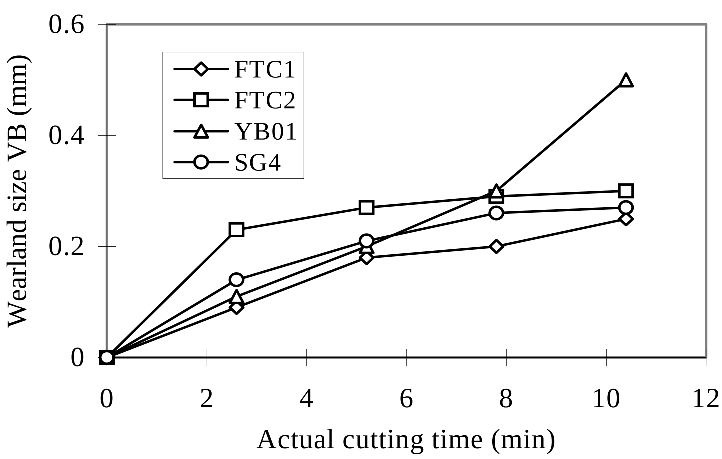

Fig. 4. Tool wear vs. actual cutting time in machining T10A steel.