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論文内容要旨

Reaction-bonded silicon carbide (RB-SiC) is an important ceramic material that has a series of superior properties such as high hardness, high thermal conductivity and chemical stability. RB-SiC has potential applications in manufacturing optical molding dies for aspherical lens and microlens arrays. However, RB-SiC is a typical difficult-to-machine material. Recent efforts have focused on the precision machining of RB-SiC by grinding, lapping, polishing, and their combinations. Although these methods can produce fine surface finish, the low machining efficiency and the high production cost are two major obstacles in industrial production of RB-SiC parts. Other methods, such as laser ablation and focused ion beams (FIB) milling could be used to generate micro structures, but the material removal rate and finished surface quality cannot meet the requirements in optical applications.

Compared with the above-mentioned methods, ultraprecision cutting using diamond tools has higher material removal rate and higher flexibility when fabricating complicated shapes and microstructures. However, to date, there has been no literature on ultraprecision cutting of RB-SiC. The ultraprecision cutting mechanism of RB-SiC has not yet been understood.

RB-SiC is harder than most other materials except diamond, cubic boron nitride (CBN) and boron carbide (B_4C). Hence, available cutting tool materials for machining RB-SiC are very limited. Investigations on the cutting mechanism of RB-SiC with ultra hard cutting tools are therefore a very challenging issue. If effective methods for ultraprecision cutting of RB-SiC could be successfully developed, extensive industrial applications of RB-SiC can be expected.

The objective of the present dissertation is to realize the ultraprecision cutting of RB-SiC on a numerically controlled ultraprecision lathe using single crystal diamond tools. At first, the cutting mechanism of RB-SiC and the wear mechanism of diamond tool were investigated and clarified. After that, a new cutting method, namely, tool-swinging cutting method with nano-particle lubrication was proposed and the machining characteristics were investigated. The effectiveness of the proposed cutting method was verified by the ultraprecision cutting tests of RB-SiC.

The details of the experimental work and the main achievements in the present dissertation study are as follows.

(1) Cutting mechanism of RB-SiC

From the viewpoint of material microstructure, RB-SiC is a two-phase composite material consisting of interpenetrating grain networks of crystalline 6H-SiC grains and crystalline bonding silicon. The two phases are different in mechanical properties: the 6H-SiC grains are harder and the bonding silicon is softer. A set of cutting tests were performed under various conditions. We found that the cutting mechanisms of the 6H-SiC grains involve ductile cutting, cleavage cracking, and grain dislodgement. The removal behavior depends on the size and depth of the 6H-SiC grains and the bonding strength at the grain boundaries. Raman spectroscopy testing on the machined surface shows that the silicon bond underwent amorphization during cutting process, while no phase transformation occurred to 6H-SiC grains. Therefore, the ductile response of the RB-SiC workpiece is originated from dislocation-based plasticity of 6H-SiC grain.

Due to the ductile response of silicon bond and the fracture energy releasing effects at grain boundaries, large-scale fractures do not take place in cutting of RB-SiC. Experimental results showed that the machined surface roughness was less affected by tool feed rate than single crystalline materials machining, but mainly depends on the material microstructure, namely, grain size. The surface roughness in ductile machining is caused by the dislodgements of a very small amount of 6H-SiC grains. This feature enables ultraprecision cutting of RB-SiC at a very high material removal rate.

(2) Wear mechanism of diamond tools

Diamond tool wear is one of the most critical problems in machining hard and brittle materials. In the present dissertation, cutting experiments were performed using natural single-crystal diamond tools. The fundamental wear characteristics of diamond tools when cutting RB-SiC mold material were investigated.

It was found that flank wear is significant in the diamond cutting process of RB-SiC. The flank wear land consists of two regions having different wear patterns: periodical micro grooves and non-periodical scratch marks. The non-periodical scratch marks may disappear as the cutting distance increases, while the periodical grooves become deeper and deeper. The periodical micro grooves were found to be oriented along the cutting direction and the pitch between the grooves is the same as the tool feed per revolution of the workpiece. It was clarified that the groove wear is a replication of the tool feed marks on the machined surface. Raman spectroscopy performed on the flank wear land indicated that the high-pressure abrasive wear at the tool-workpiece interface dominates the wear behavior, rather than the diamond-graphite transformation as reported in literatures.

(3) Tool-swinging cutting method

We proposed a new cutting method, namely, tool-swinging cutting method that can reduce the diamond tool wear in cutting hard materials. In this method, an ultraprecision machine tool with X-, Z-axis linear tables and B-axis rotary table was used. A large-radius round-nosed diamond tool is set on the rotary B-axis table. A tool-swinging movement is realized by rotating the B-axis rotary table. Because the geometrical center of the tool edge is adjusted to be in coincidence with the swinging center of the B-axis table, by swinging the B-axis rotary table, the cutting point will keep varying along the tool edge during machining process. As a result, the cutting time for a certain cutting point becomes very short and the temperature rise at that point will be dramatically reduced.

In metal cutting, cutting fluid enters the cutting zone as a result of the kinetic action of the capillary network in tool-chip interface and forms a boundary lubrication layer by physical and chemical adsorption onto the capillary wall. However, when cutting RB-SiC, the tool-workpiece contact pressure is extremely high, so that the capillary network is hard to form, and the fluid cannot enter the cutting region. This situation, however, can be improved by tool-swinging cutting. The coolant/lubricant around the cutting zone can penetrate the tool-workpiece interface as it swings, and hence an effective cooling/lubrication can be realized at the tool-workpiece interface.

Experimental results showed that the tool-swinging cutting method significantly suppressed diamond tool wear. This cutting method enabled the improvement of the working conditions at the diamond tool tip, and therefore producing high quality optical surface on RB-SiC. The improvement in surface finish is mainly because of the reduction of the dislodgement of 6H-SiC grains from the machined surface at a reduced diamond tool wear.

(4) Nano-particle lubrication method

Lubrication is a key issue in diamond turning of hard materials. Conventionally, oil (mostly kerosene) mist is widely used in diamond turning to lubricate the cutting tool and reduce the tool wear. However, kerosene mist cannot effectively reduce the tool wear in diamond turning of RB-SiC, because the high contact pressure easily destroys the oil film at the tool-workpiece interface. In addition, the application of kerosene mist for a long time induces some other problems. For example, the floating kerosene mist in air is health hazard and the recycle system increases the total manufacturing cost.

In this dissertation, nano-particle lubrication was proposed for diamond turning of RB-SiC. Four kinds of commercially available solid particles: molybdenum disulfide, graphite fibre, copper and copper oxide were used, respectively, for lubricating in diamond turning of RB-SiC, and their effects were compared. The particle size ranges from a few tens of nanometers to hundreds of nanometers. These nano-particles were dispersed into a kind of calcium-based grease. During diamond turning, the grease containing solid particles was smeared onto the workpiece surface as a thin film. With the help of the micro unevenness on the tool face and the workpiece surface, nano-particles can be brought into the tool-workpiece interface under the help of the tool-swinging movement. Under a high contact pressure, particles can be deformed and squeezed into thin films. In this way, an extremely thin solid lubricant film can be generated at tool-workpiece interface. Results showed that the type and the concentration of the dispersed nano-particles significantly affected the lubricating performance. Cutting under the lubrication of base grease containing 10% Cu nano-particles produced the lowest surface roughness and the smallest tool wear.

To summarize, in this dissertation, cutting mechanism of RB-SiC and wear mechanism of diamond tools were clarified. By using the proposed tool-swinging cutting method and the nano-particle lubrication method, diamond tool wear was significantly suppressed and the ultraprecision cutting of RB-SiC was realized. The achievements in this work may also be effective in machining other hard materials.

論文審査結果の要旨

近年，非球面レンズやマイクロレンズアレイなどの複雑微細形状を有するガラス光学素子の需要が高まっている。これらの光学素子の多くは高温プレス成形により量産されている。高温プレス成形を行うにあたり，高硬度かつ耐熱性，離型性に優れた金型が必要である。現在，超硬合金が金型材料として用いられているが，離型膜との密着性やガラスの離型性の問題が指摘されている。一方，高温硬度，耐熱性，離型性ともに優れている反応焼結炭化珪素（SiC）が次世代金型材料として有望とされている。反応焼結 SiC の加工には，現在，研削加工や研磨加工が用いられているが，高能率な複雑微細形状加工が困難である。そこで本研究では，超精密切削加工により反応焼結 SiC を高能率加工することを目的として研究を行っている。まず反応焼結 SiC の切削における材料除去機構と工具摩耗メカニズムを明らかにし，それに基づいて新たな切削法として工具揺動切削法を提案している。さらに工具潤滑のためのナノ粒子潤滑法を提案し，工具摩耗低減および加工表面粗さの改善への有効性を実証している。その結果，高能率・高精度の切削加工を実現し，高温ガラスプレス用反応焼結 SiC 金型加工へ適用の可能性を見出している。本論文は，これらの研究成果をまとめたものであり，全編 6 章からなる。

第 1 章は緒論であり，本研究の背景，目的および構成を述べている。

第 2 章では，大曲率半径の単結晶ダイヤモンド工具を用いて，異なる条件で切削実験を行い，反応焼結 SiC の基本的な加工特性を明らかにしている。特定の条件で平滑な切削面と流れ型の切りくずが形成され，延性モード切削が可能であることを示している。一方，SiC 粒子の脱落により切削面に微小ピットが現れるため，粒子脱落を防止するためには工具摩耗の抑制が重要であることを指摘している。また，切削領域で発生する高圧力によりバインダーである Si 結晶がアモルファス構造へ相転移することを顕微レーザラマン分光法により明らかにしている。このアモルファス Si の延性が SiC 粒子の脱落抑制および延性モード切削の実現に寄与していることを見出している。これは，有益な成果である。

第 3 章では，反応焼結 SiC の切削におけるダイヤモンド工具の摩耗メカニズムを解明している。工具逃げ面に従来の超精密切削では見られなかった周期的な溝状の摩耗痕が生じることを見出している。またその摩耗痕の周期と工具送り量とが等しいことに着目し，溝状の摩耗痕は継続的な高圧摩擦により加工面の送りマークが工具逃げ面へ転写されたものであることを明らかにしている。したがって工具摩耗を低減するためには，切削点位置の連続的変化および工具逃げ面の潤滑性向上が極めて重要であることを見出した。これは，工具摩耗対策検討のために重要な知見である。

第 4 章では，切削点位置の連続的変化を実現するために，工具揺動切削法という新しい切削方式を提案している。すなわち，工具を送り方向へ移動させながら工具の曲率中心を中心に揺動させて切削を行う方法である。これにより切削点の位置が常に変化するため，切削点での切削時間が著しく短縮され，工具摩耗が大幅に低減することを確認している。また，切削面プロファイルの測定値より工具揺動誤差を推定し，NC プログラムを補正することで工具揺動切削法の高精度化を実現している。これは，加工精度向上および工具摩耗低減のために有効かつ重要な成果である。

第 5 章では，工具逃げ面の潤滑性を向上させるために，工具揺動切削法においてナノ粒子潤滑法を提案している。すなわち，ナノカーボンや金属ナノ粒子などをグリースに分散させて工作物へ塗布することで潤滑を行い，粒子の変形や破壊によって工具・工作物接触界面に固体潤滑膜を形成させて工具逃げ面の摩擦を低減するものである。実験の結果，粒子の種類や大きさおよび濃度により潤滑性能が異なり，銅ナノ粒子を用いることで工具摩耗が大幅に抑制できることを明らかにしている。これは実用化に向けた重要な成果である。

第 6 章は結論である。

以上要するに本論文は，反応焼結 SiC の切削加工特性とダイヤモンド工具の摩耗メカニズムを明らかにするとともに，工具揺動切削法とナノ粒子潤滑法の新手法を提案し，従来不可能とされていた反応焼結 SiC の超精密切削を実現するものである。本論文は反応焼結 SiC を代表とする硬脆材料の超精密切削において解決すべき問題の対応策を提示し，実用化の指針を示したもので，ナノメカニクスおよびナノ加工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。