Micro Electrical Discharge Machining of Reaction-Bonded Silicon Carbide

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論 文 内 容 要 旨

Functional micro-structures are gaining more and more importance in the industrial technologies during the last few years. For example, deep micro holes find a wide range of applications in inkjet printer nozzles, spinnerets holes, turbine blades cooling channels, diesel fuel injection nozzles, drug delivery orifices, etc. Another important example is microlens arrays. The ability of microlens arrays to focus incident light into a series of beam spots makes them useful as important optical elements that are widely used in the area of optoelectronic and optical communications. Due to the wide applications of these functional micro-structures in optical, biomedical engineering and microelectromechanical systems (MEMS), micro fabrication techniques have gained growing interest from researchers and engineers.

Recently, the use of reaction-bonded silicon carbide (RB-SiC) as a material in manufacturing optical molding dies for aspherical lenses and microlens arrays has become a new research focus, due to its superior material properties, such as high hardness and strength at elevated temperature, high thermal conductivity, chemical stability, wear resistance and low density. However, due to its high hardness (Vickers hardness 25-35 GPa), it is typically difficult to be machined. Although abrasive machining processes, such as lapping, polishing and grinding can produce a fine surface finish, but the machining efficiency is low and the production cost is high. Diamond cutting is able to produce a high material removal rate, but the severe tool wear in diamond cutting of RB-SiC is the main obstacle that limits its wide application in the industry. Compared to the aforementioned methods, micro electrical discharge machining (micro-EDM) has emerged as a possibly effective machining tool to fabricate complex micro-structures on hard and difficult-to-cut materials like RB-SiC. However, the use of conventional micro-EDM alone to obtain micro-structures with good surface finish and high form accuracy in RB-SiC, is still a challenging issue. The high resistivity of the RB-SiC workpiece is the main limiting factor for the discharge current of micro-EDM, which directly affects the machining efficiency of RB-SiC.

The main objective of this study is to develop hybrid machining processes based on micro-EDM for improving the machinability and surface finish of RB-SiC. Carbon nanofibers assisted micro-EDM was proposed to replace the conventional micro-EDM. The effects of carbon nanofibers addition in the dielectric fluid were confirmed experimentally. The machining mechanism and the material migration phenomenon with the addition of carbon nanofibers were investigated and clarified. Next, a novel machining process, namely hybrid micro-EDM process by combining ultrasonic cavitation and carbon nanofibers was proposed, in order to improve the machining efficiency of RB-SiC ceramic material and to prevent from tool material deposition on workpiece. The effectiveness of the hybrid process was verified through the fabrication of micro-structures on RB-SiC.

This thesis consists of five chapters. Chapter 1 gives an overview of the background of this research. Firstly, an introduction of the RB-SiC ceramic material, including the fabrication process, material properties, applications and previous machining processes of RB-SiC material were given. EDM was chosen as a method to fabricate micro-structures on the RB-SiC, which can overcome the shortcomings of the abrasive machining process Then, an overview of the principle of micro-EDM/EDM process was discussed. The problem of machining RB-SiC by using conventional EDM was also pointed out. Some recent developments for enhancing the machinability of hard and brittle ceramic materials by micro-EDM/EDM were reviewed. Finally the objectives and organization of this thesis were stated.

Micro-EDM is primarily an electro-thermal machining process for conductive material. However, the RB-SiC that was used in this study possesses very low conductivity, which made the machining process unstable. This problem becomes more pronounced during the fabrication of micro deep holes and other micro-structures such as micro dimples and micro grooves. Therefore, in Chapter 2, carbon nanofiber assisted micro-EDM was proposed. In this process, carbon nanofibers measuring 150 nm in diameter and 6-8 μm in length were added into the dielectric fluid. Unlike the conventional EDM, carbon nanofibers can arrange themselves in the form of micro chains and interlock to each other, which help to form bridging networks between the electrode and the workpiece. Furthermore, the excellent electrical conductivity of carbon nanofiber (10^{-4} Ωcm) also reduces the insulating strength of the dielectric fluid. To verify the proposed method, firstly, simulation of electric field distribution and direction of the electric force were conducted with a commercial finite element analysis (FEA) software package, COMSOL Multiphysics. It is expected that under the influence of electric force, carbon nanofibers will be concentrated around both electrodes, and will align themselves in the form of chain in the direction of flow of current. The effect of carbon nanofiber on gap width was then studied analytically and verified through preliminary experiments. The experimental results were in good agreement with the analytical study, where carbon nanofibers were more effective in increasing the spark gap and material removal rate of RB-SiC compared to spherical carbon powders. Next, the changes in electro discharging behavior, material removal rate, electrode wear ratio, electrode geometry, spark gap, surface finish, surface topography and surface damage with carbon nanofiber concentration were examined experimentally. It was found that the addition of carbon nanofiber not only improved the electro discharge frequency, material removal rate, discharge gap and surface finish, but also reduced the electrode wear and electrode tip concavity. Micropores and microcracks were found on the machined surface, and the mechanism of micropores formation was different from that in micro EDM of conductive metals. Bidirectional material migrations between the electrode and the workpiece surface were also detected, and the migration behavior was strongly suppressed by carbon nanofiber addition. Adhesion of carbon nanofibers to the workpiece surface occurred, which contributed to the improvement of electro discharge machinability.

Material migration between electrode and workpiece is difficult to be avoided during EDM processes. Especially when performing EDM in the micro/nano scale, the effect of material migration may play an important role from the viewpoint of mechanical and physical properties of the machined surface. In order to clarify its fundamental mechanism, in Chapter 3, material migration between tool electrode and workpiece material in micro-EDM of RB-SiC was experimentally investigated. The microstructural changes of workpiece and tungsten tool electrode were examined using scanning electron microscopy (SEM), cross-sectional transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDX) under various voltage, capacitance and carbon nanofiber concentration in the dielectric fluid. The RB-SiC that was used in this research, consists of crystalline 6H-SiC grains and crystalline bonding silicon. During the EDM process, the Si matrix, in conjunction with sintering agents, possesses a higher electrical conductivity than the 6H-SiC grains, so it was preferentially removed by melting and vaporization, leaving craters on the surface. The melted tungsten electrode particles were deposited intensively inside the discharge-induced craters on the RB-SiC surface as amorphous structure forming micro particles, and on flat surface region as a thin interdiffusion layer of poly-crystalline structure. The formation mechanism of the subsurface layer in this work was distinctly different from those in mechanical machining processes such as diamond turning, which mainly phase-transformed from the bulk material by mechanical stresses. Deposition of carbon element on tool electrode was also detected, indicating possible material migration to the tool electrode from workpiece material, carbon nanofibers and dielectric oil. Material deposition rate was strongly affected by workpiece surface roughness, voltage and capacitance of the electrical discharge circuit. For reducing the migration and deposition of tool material, the capacitance should be kept as low as possible and the voltage at moderately high level. Adding carbon nanofibers into the dielectric fluid at a concentration of 0.06 g/L was helpful. These findings are useful for improving the surface integrity and purity of RB-SiC in micro-EDM.

In micro-EDM, due to the narrow sparking gap, the removal of debris is remaining a challenging issue, especially in deep holes machining and fine finishing with lower discharge energy. The deposition of tool material on the workpiece surface not only caused surface contamination, but also deteriorated the surface finish of the workpiece. Conventionally, orbital electrode actuation, flushing, planetary movement of electrode, ultrasonic vibration, etc were used to overcome these problems. In Chapter 4, in order to suppress the tool material deposition and improve the machining efficiency of RB-SiC ceramic material, a new machining method, namely hybrid EDM process by combining ultrasonic cavitation and carbon nanofibers was proposed. In this method, suitable amount of carbon nanofibers were added and mixed uniformly in the dielectric fluid. An oscillator horn was placed into the compound dielectric fluid and ultrasonic vibration was used to generate cavitation to assist micro electrical discharge machining. For comparison, another two types of micro-EDM tests were then carried out, namely, carbon nanofibers addition in EDM oil only, and ultrasonic cavitation in pure EDM oil. Changes of hole depth, hole geometry, surface topography, machining stability and tool material deposition rate under various machining conditions were investigated experimentally. The results show that the ultrasonic vibration-induced cloud cavitation was very helpful for increasing sparking gap and removing debris, especially when carbon nanofibers were added into the dielectric fluid. The combination of ultrasonic cavitation and carbon nanofibers can improve the maximum hole depth, form accuracy, and surface finish of micro holes to a significant degree. The tool material deposition rate was strongly affected by the ultrasonic vibration amplitude and the distance between the oscillator and workpiece during fine finishing. The main mechanism for removing the debris from the sparking gap was through the oscillation of the cloud cavitation, rather than the collapse of micro bubbles. The cloud cavitation tends to oscillate at the working area due to the pressure fluctuation in dielectric fluid which was induced by low intensity ultrasonic waves. In a cloud cavitation, the nonlinear bubble dynamics produced nonlinear interactive effects which caused cascading of fluctuation energy. This fluctuating energy was helpful to flush out the debris from the working gap. As test pieces, aspect ratio of 21.7 micro deep hole was successfully fabricated on RB-SiC at a high machining speed. Under fine finishing conditions, micro dimples with good cross-sectional profile and minimum tungsten deposition were successfully obtained. The proposed hybrid EDM process has been demonstrated to be helpful for fabricating micro-structures on hard brittle ceramic materials.

In Chapter 5, the general conclusions of this research were summarized.

As a summary, in this dissertation, carbon nanofibers assisted micro-EDM has been developed to enhance the machinability of low conductivity RB-SiC ceramic materials. Material migration phenomena during the micro-EDM process were clarified. The optimal conditions to control the material migration in micro-EDM of ceramic materials and to improve the finished surface topography and surface integrity were confirmed. By using the proposed hybrid EDM process with combination of ultrasonic cavitation and addition of carbon nanofibers in dielectric fluid, tool material deposition was significantly suppressed and machining efficiency was improved 5-7 times compared to the one obtained with merely ultrasonic cavitation or carbon nanofibers addition. With this method, high aspect ratio micro holes and good cross-sectional profile micro dimples with minimum tungsten deposition were successfully fabricated on hard and brittle RB-SiC ceramic material. By applying the new process proposed in this dissertation, the production cycle and cost involved may significantly reduce compared to the conventional process.

論文審査結果の要旨

近年，光学分野や医療分野をはじめとする様々な分野において，材料（製品）の表面に微細な構造を作製し，製品そのものを高機能化させる試みがなされており，そのような微細な構造を作製するための超精密加工プロセスに対する需要が高まっている。特に硬脆材料であるセラミックス材料に対して構造を作製する場合には，機械加工プロセスであるダイヤモンド切削や研削，ラッピングやポリッシングなどのプロセスに代わってマイクロ放電加工（micro-EDM）法の利用が注目されている。ただし導電性の低いセラミックス材料などを対象とした場合，通常の micro-EDM 法では加工自体も難しく，高精度化や高品位化には課題が残されている。そこで本論文ではカーボンナノファイバー（CNFs）を用いてマイクロ放電加工を行う新たな手法を提案し，その効果について実験的検証を行っている。また，仕上げ加工プロセス中に加工面に工具材料が付着し，表面品位が低下するといった課題に対しては，CNFs を用いるのに加えて超音波キャビテーションを援用したハイブリッドマイクロ放電加工プロセスを提案し，その可能性についても検討している。これらの手法を用いることにより，これまで放電加工の適用が難しいとされてきた反応焼結炭化珪素（RB-SiC）に対して，高効率かつ高精度な加工を可能としている。また，加工面への工具材料の付着を抑制し，表面の高品位化にも成功している。さらに，同材料に対して高アスペクト比の微細穴の作製およびマイクロレンズアレイ用の金型を想定したマイクロディンプルの作製にも成功している。本論文は，これらの研究成果をまとめたもので，全編 5 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，RB-SiC のマイクロ放電加工を可能とするため，CNFs を用いた新たな加工方法を提案し，その効果について実験的に検証している。CNFs を用いた手法で生じる放電現象について，そのメカニズムを解明するとともに，本手法を用いた際の材料除去率，電極摩耗率，スパークギャップ，表面粗さ，表面形状および表面損傷に及ぼす影響について実験的に検討を行うことで，その有効性を明らかにしている。また，CNFs の添加量を系統的に変化させて実験を行うことにより，CNFs 添加量が加工面性状に及ぼす影響についても明らかにしている。これはこれまでにない有益な成果である。

第 3 章では，マイクロ放電加工を行った際に表面品位の低下をもたらす加工面への工具材料の付着現象について着目し，第 2 章で提案した手法についてその効果を実験的に検証している。CNFs の添加量や加工条件を適正に設定することにより，加工面への工具材料の付着量を大幅に抑制することに成功している。また工具材料が加工面に付着する現象について，そのメカニズムを明らかにしており，重要な成果である。

第 4 章では，RB-SiC に対するマイクロ放電加工の更なる高効率化・高精度化および高品位化を目的として，CNFs の添加に加えて超音波キャビテーションを援用したハイブリッド加工プロセスを提案し，その効果について実験的に検証している。本手法を用いることにより微細穴加工時の加工効率および加工安定性が向上し，加工面の形状精度や表面粗さが改善することを明らかとしている。その原因については，提案するハイブリッド加工プロセス時の特徴的なデブリの除去現象から考察を行っており，有益な知見を得ている。超音波キャビテーションを援用する際の加工条件が加工面性状に及ぼす影響についても実験的に検証を行っており，加工条件と得られる加工面性状の関係性について明らかにしている。また，得られた知見をもとに高アスペクト比の微細穴およびマイクロディンプルの高効率・高精度・高品位加工にも成功している。これは本プロセスの実用化に向けた重要な成果である。

第 5 章は結論である。

以上要するに本論文は，硬脆材料に対して微細な構造を高効率・高精度かつ高品位に作製するための新たなマイクロ放電加工法を提案するものである。本手法は，これまでの手法では適用が難しかった導電性の低いセラミックス材料に対しても有効であり工学的に高い意義を有する。また本手法で得られた材料除去に関する知見は，放電加工における新たな加工メカニズムとして有益な知見であり学術的にも意義深く，機械システムデザイン工学およびナノ精度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。