氏名　曹　建国
授与学位　博士（工学）
学位授与年月日　平成 26 年 9 月 25 日
学位授与の根拠法規　学位規則第４条第１項
研究科専攻　秋田県立大学大学院システム科学技術研究科
博士後期課程総合システム科学専攻
学位論文題目　Ultra-fine internal grinding of SiC ceramics with the assistance of ultrasonic vibration
(超音波を援用した SiC セラミックス内面の超精密加工の研究)

指導教員　教　授　呉　勇波

論文審査委員　主査　教　授　呉　勇波

副査　教　授　神　雅彦(日本工業大学)　教　授　水野　衛

教　授　尾藤　輝夫

論文内容要旨

In this study, toward the development of an alternative machining method for the internal grinding of SiC ceramics, the UAIG technique is applied to the internal grinding of SiC ceramics. For this purpose, an experimental rig was constructed by installing an ultrasonic spindle onto a CNC internal grinder and experimental investigations on the machining characteristics of SiC ceramics workpiece were performed on the constructed rig. In order to optimize grinding parameters to achieve high product quality and productivity, a grinding force model for UAIG of SiC ceramics has been developed. Further, to deeply investigate the material removal mechanism in ultrasonic assisted internal grinding of SiC ceramics, the ultrasonic assisted scratching (UAS) tests were performed on SiC ceramics with a self-designed ultrasonic unit. Besides, a validated simulation model is developed to further investigate material removal mechanism in UAS. The obtained results of this study can be summarized as following:

In chapter 1, prevailing technologies, i.e., ultrasonic assisted grinding and ultrasonic assisted internal grinding was outlined. The classical and recent works were reviewed. The motivations for this study were outlined.

In chapter 2, the processing principal of UAIG was introduced. The experiment apparatus and experiment details were presented.

In chapter 3, experimental investigations on the machining characteristics of SiC ceramics workpiece were performed on the constructed rig. The conclusions are obtained as follows:

(1) The normal and tangential grinding force in UAIG are significantly reduced compared with those in CIG. This

is the valuable information for the application of UAIG technique to the internal grinding of SiC ceramics.

(2) The greater improvement of the form accuracy and surface quality are achieved in UAIG compared with those in CIG

(3) Abrasive grain protrusions are observed sufficiently in UAIG. The pullout of grain is considered as the main wheel wear mechanism in CIG while the micro-fracture as well as the slight grain pullout are the dominant mechanisms in UAIG. Observation of subsurface damage shows the fracture depth is decreased and cracks are alleviated.

In chapter 4, a grinding force model for UAIG of SiC ceramics has been developed. The model incorporates input variables of the grinding process and the UV. Comparing the forces predicted using the developed model with the experimental ones shows that the variation tendencies and the quantitative values of the predicted forces agreed reasonably with those of the experimental ones. Relationships between the input variables and the grinding forces in UAIG can be concluded as following:

(1) The grinding forces increase in the grinding process. Furthermore, the grinding forces are reduced in the UAIG compared to CIG, which is attributed to the formation of the smaller the undeformed chip cross sectional area.

(2) The grinding forces increase with the increasing of the workpiece rotational speed n_w and the wheel infeed rate V_c, whereas decrease with the increasing of the wheel rotational speed n_g, the UV amplitude A_u and the oscillation frequency f_o; the influence of the wheel rotational speed n_g, the workpiece rotational speed n_w and the wheel infeed rate V_c on grinding force are much pronounced, whereas that of the UV amplitude A_u and the oscillation frequency f_o are not very noticeable.

(3) The force reduction of UV can be enhanced either by decreasing the wheel rotational speed n_g, the workpiece rotational speed n_w and the wheel infeed rate V_c or increasing the UV amplitude A_u and the oscillation frequency f_o.

In chapter 5, to comprehend the material removal mechanism in the ultrasonic-assisted grinding of SiC ceramics, an ultrasonic-assisted scratching (UAS) test involving SiC ceramics specimen was performed on an in-house-produced experimental setup. The material removal characteristics in the UAS test were compared to the conventional scratching (CS) test without ultrasonic vibration. The results and conclusion can be summarized as follows:

(1) Both in CS and UAS processes, three types of material deformation/fracture are successively generated along the scratching trace: the ductile removal mode, ductile–brittle transition mode, and brittle removal mode; the scratching groove formed appears straight in the CS process while it is sinusoidal in the UAS process.

(2) The UV in the direction that vertical to work-surface strongly contributes to the material removal, whereas the UV in the direction that parallel to work-surface only results in variation of the cutting trace and hardly contributes to the material removal in the UAS process.

(3) The cutting ability of the tool was significantly improved by the assistance of the UV. Furthermore, the critical depth of cut is increased from 0.08 μm in CS to 0.125 μm in UAS, which is an increase of 56.25%.

(4) The deformation of the SiC ceramics in the UAS process is equivalent to the combined effect of dynamic cutting with a tangential scratch velocity and UV.

In chapter 6, in order to high accuracy internal grinding of SiC ceramics, the probability of internal grinding of SiC ceramics in ductile mode and grinding efficiency were observed. The results showed that critical depth of cut is increased in UAIG compared with that in conventional internal grinding (CIG), meaning that ductile mode grinding is easily achieved in UAIG; grinding efficiency is higher in brittle grinding mode compared to that in ductile grinding mode in UAIG. In addition, high accuracy can be achieved by UAIG under the recommended experiment conditions.

論文提出者氏名	曹　建国
論文題目	Ultra-fine Internal Grinding of SiC Ceramics with the Assistance of Ultrasonic Vibration （超音波を援用したSiCセラミックス内面の超精密加工の研究）
指導教員	呉　勇波
論文審査委員	主査　教　授　呉　勇波 副査　教　授　神　雅彦　　教　授　水野　衛 （日本工業大学工学部機械工学科） 教　授　尾藤　輝夫

論文審査結果要旨

本論文は，砥石に軸方向の超音波微振動を付与しながら SiC セラミックスの円筒内面を高能率で超精密に研削加工する技術の開発を目指したものである．近年，ガラスレンズのモールドプレス成形に用いる胴型など円筒内面を有する SiC セラミックス部材に対する需要が急増し，その内面を高能率で精密に加工するニーズが高まりつつある．従来加工技術では，粗研削・精密研磨といった 2 工程が施され，加工時間が長く，加工精度の達成が難しいといった問題があった．そこで本論文では，ダイヤモンド砥石に軸方向の超音波微振動を付与して SiC セラミックスの内面を高能率で精密に研削加工する手法を提案した．超音波スピンドルを中心要素とする実験装置を構築した上，超音波援用による加工特性の向上効果を確認した．また，加工特性の最適化を図るのに欠かせない研削抵抗のモデリングや超音波援用下の材料除去メカニズムについて理論的実験的に検討した．なお，本提案技術の実用化を目指し，要求加工精度と能率を満たすような加工条件も特定した．全文は序論と結論を含め 7 章からなる．

第 1 章は序論であり，研究背景や目的および論文構成について述べている．第 2 章では，加工原理をはじめ，超音波スピンドルと精密ワークチャッキング機構を備えた精密内面研削実験装置の構築とその動作試験および実験方法を説明している．第 3 章では，超音波援用効果の確認を目的に超音波有無における加工特性の体系的実験調査を行った．その結果，超音波を援用すると研削抵抗が数十パーセント以上低減され，加工物の形状精度と面粗さが大きく向上し，内部欠陥も大幅に減少することが明らかになった．第 4，5 章ではそれぞれプロセスの最適化を図るのに重要な研削抵抗のモデリングや材料除去メカニズムの解明について解析的実験的に検討した．その結果，加工条件と研削抵抗の関係を明らかにし研削抵抗の予測が可能になった．特に材料除去メカニズム検討の結果，延性/脆性モード加工の遷移点における臨界切込み深さが超音波の援用によって 50%以上大きくなることとその理由を明らかにした．第 6 章では，本提案技術の実用化を目指して延性モードの加工が行われる条件での加工の高精度化高能率化について検討を進め，要求精度と能率を満たすような加工条件を特定することができた．第 7 章では本研究で得た結果をまとめ，今後の研究課題を提起している．

以上，本論文は，SiC セラミックスの内面加工においてこれまでにない新しい加工法の提案から基礎加工特性の体系的調査と加工メカニズムの解明まで多くの知見と成果を得ており，工学的価値が高いだけではなく実用化への道筋も示した．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．