氏　　　　　　名	馮　銘	〈※枠内は 12 ポイント〉
授　与　学　位	博士（工学）	
学 位 授 与 年 月 日	令和元年 3 月 24 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		
指　導　教　員	教　授　尾藤　輝夫	
論 文 審 査 委 員	主査　教　授　尾藤　輝夫	
	副査　教　授　鈴木　庸久	教　授　島田　邦雄
	教　授　呉　勇波	准教授

※本研究科以外に所属する場合はその所属を括弧書きすること

論 文 内 容 要 旨　※(20 ポイント)

Aspheric elements have become essential optical surfaces for modifying optical systems due to their abilities to enhance the imaging quality. However, the tool marks and sub-damage were remained inevitably by the pre-manufacture techniques, such as the single point diamond turning (SDPT) and the high precision grinding. In order to improve the surface quality, the polishing process was demanded to eliminate these defects. The magnetic field-assisted polishing method was prominent for this purpose. A magnetic compound fluid (MCF) was developed by compositing a magnetic field (MF) and a magnetorheological (MR) fluid. MCFs exhibited higher magnetic pressure and apparent viscosity than MFs and a better dispersity of nonmagnetic particles than MR fluids under a magnetic field while maintaining a fluid-like behavior. The MCF slurry contains usually carbonyl-iron-particles (CIPs), water-based MF with nm-sized magnetite particles, abrasive particles, and α-cellulose. However, MCF slurry has not been used to polish aspheric surfaces, due to the complex material removal profile induced by the conventional polishing methods. By the inspiration of conventional MCF polishing tools, i.e., the mountain-shaped MCF tool and MCF wheel, a novel doughnut-shaped MCF tool was proposed for polishing aspheric surfaces. Under a rotary magnetic field which was generated by the revolution of the eccentrically located ring-shaped magnet, the magnetic lines of force constantly revolved around the MCF carrier, leading the clusters formed by CIPs to alert their orientations to stir abrasive particles. The renewing working area prolonged the life of the MCF tool to a limited extent. In this study, polishing with the novel MCF polishing tool under the rotary magnetic field was extensively studied from the investigation on feasibility polishing, the fundamental properties of the MCF tool (including the formation process, the optimal geometry of the MCF tool, and behavior of CIPs and APs), the evolution and equivalent control law of surface roughness (including the indentation model for a single abrasive particle, polishing forces, and prediction model for surface roughness), and the investigation experimentally on the effect of parameters on removal of material/tool marks and surface quality. According to the results, the aspheric surface was polished successfully.

The fundamental properties of rheological behaviors of MCF slurry were studied, which demonstrated that the shear stress and viscosity were affected significantly by CIPs concentration and magnetic field strength. Thus, the polishing principle with the novel polishing tool was given out according to the properties of the MCF slurry, and the experimental setup was constructed. The results of the feasibility polishing experiments showed that the top tip of the MCF tool was located at a distance D to the revolution center of the MCF tool and performed better ability on removing material. The D could be obtained by using $D = (d_i + d_o)/4$, i.e., the middle portion of the working area. Simultaneously, the location and gesture control laws for polishing were given out. Because the workpiece was polished to the nano-precision scale in the experiments, it was certain that this method was potential to polished materials.

The variation process of external MCF slurry, terminal shape and the formation time were investigated for obtaining the perfect MCF tool under various process parameters, namely magnet eccentricity r_e, supplied MCF slurry amount V, MCF slurry carrier rotational speed n_c, and magnet revolution speed n_m. The internal structure of the MCF tool was observed, based on which the behavior of CIPs and APs were thereby confirmed through theoretical analysis and polishing experiments. The model of material removal was proposed. The results showed that a perfect MCF tool could be obtained when the eccentricity r_e, the rotation speed of the MCF carrier n_c, the revolution speed of the magnet n_m, and the amount of MCF slurry supplied V were proper. The CIPs were gathered to form the ferric clusters along the magnetic flux lines. The Aps, at a given working gap, can squeeze the work-surface. The squeezing action was much more intense when larger APs and the MCF slurry with a higher magnetization were employed. The material removal model suggested that the material was removed due to the APs and the relative motion between the work-surface and APs.

In order to study the evolution and equivalent control law of surface roughness, the motion analysis, and indentation model were established theoretically by explaining in detail the normal force and tangential force induced by the MCF tool. Simultaneously, numerical analysis for predicting the surface roughness under variable parameters was conducted. The prediction model on surface roughness was verified by a series of experiments. As a result, the relationship between parameters and surface roughness was obtained, thus, the surface roughness can be predicted by giving the proper parameters.

The investigation on polishing aspheric surfaces was conducted experimentally. The representative material removal profile on the generatrix, the process of removing tool marks, and typical surface roughness were investigated. The effects of parameters, including working gap h, the revolution speed of MCF carrier n_c, amount of MCF slurry supplied, CIPs concentration and APs size on polishing performance were conducted. With the optimized conditions, the aspheric surface was polished successfully. As a result, a V-shaped generatrix was obtained on the polished conic surface. A similar surface roughness at the circumference and different surface roughness on the generatrix were found. The tool marks composited of periodic peaks and valleys with relatively low frequencies were diminished gradually with the polishing time. A smaller working gap was proper for polishing. The 1 mm of working gap h was selected in the experiments. Higher revolution speed of MCF carrier n_c and the larger amount of MCF slurry were applied, and then a larger material removal rate, larger polishing area, and better surface roughness were achieved. Better performance on the material/tool marks removal rate when a higher CIPs concentration was applied. However, the best surface quality was attained with the CIPs concentration of 45 wt.% in this study, rather than 55 or 35 wt.%. Larger APs were beneficial for obtaining higher material/tool marks removal rates. However, a better surface quality was achieved when the APs of 1 μm in diameter were preferred rather than 0.5 or 2 μm. The aspheric surface was polished successfully without the tool marks on the surface. Furthermore, the shape of the workpiece was kept in a favorable extent.

According to the above results, the magnetic field-assisted polishing using the novel MCF tool is a promising technique for the nano-precision finishing of aspheric surfaces.

論文提出者氏名	馮　銘
論　文　題　目	Investigation on Aspheric Surface Polishing with a Doughnut-Shaped Magnetic Compound Fluid (MCF) Tool (ドーナツ型磁気混合流体(MCF)ツールを用いた非球面研磨の研究)
指　導　教　員	尾藤　輝夫
論文審査委員	主査　教　授　尾藤　輝夫　㊞ 副査　教　授　鈴木　庸久　㊞　　教　授　島田　邦雄　㊞ (福島大学) 教　授　呉　勇波　㊞ (南方科技大学)

論文審査結果要旨

本論文は、ドーナツ型磁気混合流体(MCF)ツールを提案し、それを用いた非球面の超精密研磨技術を確立するための基礎研究の成果を取りまとめたものである。本論文は全 6 章で構成されている。

第 1 章では緒論として、本研究の背景や目的について述べている。非球面光学素子は、結像品質が高く、構造が簡単なため、高精度光学システムに不可欠となっている。その加工製作では、ダイヤモンド切削と超精密研削などの後に研磨を施すことによってツールマークや表面損傷を無くすことが重要であり、この点で MCF ツールの有効性が従来の研究で確認されている。しかし、従来のマウンテン型 MCF ツールは平面研磨に適しているが、非球面など複雑な表面研磨では研磨対象の形状精度を維持することが難しい。そこで本論文では、MCF ツールをドーナツ型にすると研磨領域が絞られ、形状精度を維持しやすい点に着目し、ドーナツ型 MCF ツールを提案して非球面研磨に適用した際の基礎加工特性を調べている。第 2 章では、まず実験装置を構築して、ドーナツ型 MCF ツールの形状や寸法に及ぼす形成条件の影響を調べ、非球面研磨に適したツールの形状と寸法を特定している。第 3 章では、ドーナツ型 MCF ツールの性質を把握し、研磨条件設定の指針を得るために、その内部構造を観察して内部組織の挙動を検討している。第 4 章では、材料除去機構を理論的に検討した上、表面粗さの予測モデルを確立し、実験によってそのモデルの有効性を検証した。第 5 章では、円錐面や非球面の研磨実験を試み、加工条件が材料除去率、面粗さ、形状精度に及ぼす影響を体系的に調査している。その結果、形状精度や面粗さで最適な条件を見出し、面粗さが 10 nm Ra 程度、形状維持率が 99%以上の高精度な非球面を得ることができた。第 6 章では、これまで得られた成果をまとめ、今後の課題を提起している。

本論文はこれまでにない非球面の超精密研磨法の提案から基礎加工特性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、工学的価値が高く実用化への道筋も期待できる。また研究業績として、本研究課題と関連する査読付き学術誌論文 4 編(公表済み 2 編、掲載可 1 編、査読中 1 編)、国際会議発表 9 件、国内学会発表 2 件を公表している。

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。