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論 文 内 容 要 旨

A magnetic compound fluid (MCF) is developed by mixing a magnetic field (MF) and a magnetorheological (MR) fluid. An MCF contains not only μm-sized iron particles but also nm-sized magnetite particles whereas there are no nm-sized magnetite particles within the MR fluid. MCFs exhibit higher magnetic pressure and apparent viscosity than MFs and a more stable distribution of particles than MR fluids under a magnetic field, while maintaining a fluid-like behaviour. An MCF slurry is generally composed of carbonyl-iron-particle (CIP), water based MF, abrasive particles and α-cellulose. In this study, a rotary magnetic field was employed. The magnetic flux density is constant but the magnetic lines of force constantly revolve around the magnet holder axis. In this thesis work, polishing with MCF slurry under a rotary magnetic field was extensively studied from the work life, dynamic behaviours, mechanical characteristics of MCF slurry, the application of MCF polishing in soft magnetic as well as non-magnetic materials, and material removal behaviours.

Work life of MCF slurry (in the absence of α-cellulose) was studied through the spot polishing tests of optical glass, namely fused silica (FS) and borosilicate glass (BK7). It is observed that MCF slurry of only a volume of 1 mL keeps stable material removal rate (*MRR*) (depth removal rate of ~0.0243 μm/min and volume removal rate of ~0.07 mm^3/min) and attains smooth surfaces inside spots ~1 nm over a relative long spot polishing period of 25 min. The removal function is depended on the compositions of MCF slurry and insensitive to the two glasses.

To clarify the behavious of MCF slurry under a rotary magnetic field, the effects of process parameters (namely magnet eccentricity r, magnet revolution speed n_m and MCF slurry supplied volume v) on the time T required for forming the slurry to its final shape, and the dimensions (namely diameter W and the maximal length $H_{\max}$) of the final shape were investigated. The normal and shear forces were simultaneously measured and the effects of process parameters (namely magnet revolution speed n_m, MCF slurry carrier rotational speed n_c and working gap Δ) were studied. It is noted that MCF slurry achieves a clear-cut terminal shape and the shape and dimensions of its terminal are repeated periodically with the magnet revolution at the same frequency n_m. The time T decreases with the increases in the magnet eccentricity r (significantly if $r < 4.5$ mm) and the speed n_m, and rises up as the supplied slurry volume v increases. Both dimensions changes significantly with the variation in the magnet eccentricity r, while they are insensitive to the magnet revolution speed n_m. The W is maximized and the $H_{\max}$ is minimized both at $r = 4.5$ mm, and the $H_{\max}$ shows only a little increase with the increase in the supplied MCF slurry volume v. Therefore, the maximal contribution is made by magnet eccentricity on behaviours of MCF slurry, followed by MCF slurry supplied volume, whereas minimal contribution is noted by magnet revolution speed. Both forces are significantly dominated by the working gap, slightly governed by the MCF slurry carrier rotational speed and insensitive to the magnet revolution speed. More uniform distribution of abrasive particles and slurry and a better surface finish are obtained under a rotary magnetic field than under a static one.

The rotary magnetic field disperses MCF slurry uniformly during polishing, which favors nano-precision finishing. However, CIP within the MCF slurry has poor ability against corrosion in a common water based carrier. Nano-precision polishing of polymethyl methacrylate (PMMA) was performed with a novel zirconia (ZrO_2)-coated CIP based MCF slurry. Polishing performances of this kind of MCF slurry, namely surface roughness and normal force, were discussed by comparing the ZrO_2-coated CIP based MCF/MRF slurry with the HQ CIP based MCF slurry. In the presence of abrasive particles (Al_2O_3), ZrO_2-coated CIP based MCF slurry does not perform better than non-coated HQ CIP based one. In the absence of abrasive particles, the ZrO_2-coated CIP based MCF slurry behaves better than the MRF slurry; ZrO_2-coated CIP concentration should be less than a certain value (in the current work, 70 wt.%), otherwise MCF slurry shows bad particle dispersion and is easily dried, resulting in the loss of its polishing ability.

As an extension of the application for ZrO_2-coated CIP based MCF slurry, the single crystal diamond turning (SCDT) Ni-P plating mold was polished using this kind of MCF slurry in order to eliminate SCDT-induced tool marks. By contrast, an HQ CIP based MCF slurry was used as well. Spot polishing without relative motion between the centre of the MCF carrier and workpiece was first carried out using both slurries. Scanning polishing with the MCF carrier moving along a motion path was then carried out using only the ZrO_2-coated CIP based MCF slurry. Although both slurries removed the SCDT-induced tool marks on the work surface, the MCF slurry containing relatively large Al_2O_3 abrasive particles left scratches and frequently caused CIPs to be embedded in the Ni-P plating surface, which inversely worsened the work surface roughness. In contrast, the MCF slurry that contains relatively small ZrO_2 abrasive particles resulted in a work surface roughness that was slightly improved, without scratches or the embedding of particles. The cross-sectional profile of the polishing spot manifests a characteristic symmetrical W-shape. The induced scratches display a dot-shape at the spot centre and the lengths of the scratches increase with the increase in the distance from the spot centre. In scanning polishing, the W-shaped polishing spot moves along the designed scanning path and the overlap of the instantaneous W-shaped spots occurs, which significantly improved the flatness of the Ni-P plating layer from 0.2 μm to 0.1 μm. In addition, almost all of the particles can move relative to the work surface, and the surface roughness of the Ni-P plating layer was improved without causing scratches or the embedding of particles. The preliminary results show that MCF polishing is applicable to the nano-level finishing of soft magnetic materials.

To elucidate the material removal behaviour in MCF polishing, the normal and shear forces generated in the polishing zone during polishing were measured. From these measurements, the distributions of pressure P and shear stress τ were obtained. The material removal rate (*MRR*) was investigated through spot polishing of borosilicate glass. The *MRR* distribution was obtained and the characteristics of the removal function (namely the polishing spot), i.e. the radius R, maximal depth dRR_{max} and its position d_{max}, volume *VRR* of the polishing spot, were also studied. The effects of three process parameters, namely magnet revolution speed, MCF carrier rotational speed and working gap, on pressure P, shear stress τ and the *MRR* were first investigated. The results revealed that P is higher near the centre of the interacting area, (i.e. the polishing spot centre) and the point of maximum shear stress τ appears at about 5 mm from the polishing spot centre. All of P, τ and *MRR* are sensitive to MCF carrier rotational speed and working gap but insensitive to magnet revolution speed. Shear stress is more sensitive to these process parameters than the pressure. Cross-sectional profiles of the polishing spots exhibit a characteristic symmetric W-shape; material removals are minimal at the spot centre and maximal at approximately 8.2–10.2 mm from the spot centre depending on the process parameters. *MRR* is proportional to the MCF carrier rotational speed and is negatively correlated with working gap. An *MRR* model involving both the pressure and shear stress in MCF polishing is proposed. In the model, *MRR* is more dominated by shear stress than by pressure. Regarding the removal function, the effect of magnet eccentricity was also studied. The radius of the removal function only shows relative large decrease in the increase in the working gap, a little increase with the magnet eccentricity increasing from 0 to 4.5 mm, and a little increase when the concentration of α-cellulose increases from 0 wt.% to 3 wt.%.. The position d_{max} where dRR_{max} occurs becomes largest at working gap Δ of 1 mm, and is minimized at magnet eccentricity r of 3 mm and maximized at concentration of α-cellulose of 1.5 wt.% while it changes little with the variations of other process parameters. Both the depth and volume of the removal function appears insensitive to magnet revolution speed, linearly increase with the increase in the MCF slurry carrier rotational speed, linearly decrease as the working gap increases, and is maximized at magnet eccentricity r of 3 mm and maximized at concentration of α-cellulose of 3 wt.%.. In addition, the magnetic field was analysed and the structure of MCF slurry was examined to explain the characteristics of the removal function. Magnetic clusters with the MCF slurry are formed along the magnetic lines of force. The thickness of slurry is maximized in a range during polishing. The removal function is strongly related to the magnetic field distribution and the geometry and internal structure of the slurry. The maximal material removal occurs at the position where many abrasives are collected and they possess considerable relative speed to the work surface.

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論　文　題　目	Fundamental Investigation on Nano-precision Surface Finishing using MCF (Magnetic Compound Fluid) Slurry （MCF(磁気混合流体)スラリーを用いたナノレベル超平滑研磨の基礎研究）
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論文審査結果要旨

本論文は，MCF(磁気混合流体)スラリーという磁場制御型研磨剤を用いたナノレベル超平滑研磨技術を確立するための基礎研究を進めたものである．磁場制御型研磨法は，砥粒の挙動が磁場によって制御され，単位研磨剤あたりの加工能率が高い点で注目を浴びている．しかし従来では，平均粒径 10nm 程度のマグネタイト微粒子を含有した磁性流体(MF)やミクロンオーダの鉄粉を含有した磁気粘性流体(MRF）をベースにした研磨スラリーを用い，前者は砥粒の把持力が不十分で，後者は砥粒の分散性が良くないといった問題があった．本論文では両者それぞれの長所と短所を鑑みて MCF スラリーという新しい磁場制御型研磨剤にロータリ磁場を印加して研磨を施す新しい研磨法を提案し, 研磨ユニットを中心要素とする実験装置を構築した上，磁場作用下 MCF スラリーの挙動と研磨力を調べた．また，光学樹脂，Ni-P メッキ，光学ガラスの超平滑研磨を試み，これら材料の基礎研磨加工特性と材料除去メカニズムを明らかにした．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，ロータリ磁場の発生と MCF スラリーの保持を担う研磨ユニットを中心要素とする実験装置を構築し実験方法を検討したのに加え，MCF スラリーの作用寿命も評価した．第 3 章では，磁場作用下 MCF スラリーの挙動と力学特性の調査に加え, 光学ガラスの研磨テストを行いロータリ磁場の有用性について実験的に確かめた．その結果，ロータリ磁場作用下で MCF スラリーが素早く山状やドーナツ状に自己形成され，その形状と寸法は作用磁場によって調整できることが明らかになったのに加え, 静磁場と比べロータリ磁場を作用すると面粗さは約 73%と大幅に減少することもわかった. 第 4, 5 章ではそれぞれ樹脂（PMMA）と Ni-P メッキのナノレベル研磨を試み，切削や研削など前工程で発生した加工条痕を完全に消すことができるだけではなく，面粗さが 1nmRa 以下の超平滑面が得られるような加工条件も特定できた．第 6 章では光学ガラスの MCF 研磨特性を体系的に調査し，特に材料除去に支配的なのがせん断力であることを明らかにした．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，軟質の光学樹脂から硬質の光学ガラスまで各種光学材料のナノレベル超平滑研磨においてこれまでにない新しい加工法の提案からこれら材料の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．