開発された高機能なタッピングツールは、耐久性を持ち、高精度で加工が可能である。

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This thesis, which describes the systematic study on development of high functional tapping tool coated with Ni-P/abrasive particle composite film, consists of seven chapters. The principal results in these chapters are summarized as follows:

Chapter 1 describes the background and purposes of the thesis. Joining processes are an essential component of manufacturing and assembly operations. In the joining processes, screws are one of the most commonly used thread fasteners. The thread holes are machined using a tapping tool. Especially, cut tapping tools are used widely in various workpiece materials. In order to meet the need for a tapping process suitable for high machining efficiency, improvements in tapping tools are required to allow for their functioning at high cutting speeds and to extend tool service life. However, at high cutting speeds, the tapping tools cause the chip snarling and chip clogging because the tapping tool causes a decrease in the chip discharge ability. The chip discharge problems cause the damage of the workpiece materials and tool breakage. Thus, the chip snarling problem must be prevented to increase cutting speed as well as extend tool service life.

Many studies of tapping processes have been performed with the aim of improving thread hole quality and machining efficiency. Furthermore, there are many studies on hard coating and lubricant films in order to improve the tool edge strength. However, there are few studies on chip curl and chip evacuation during tapping process and there has not been a solution to the chip discharge problem. In general, the coating film on tapping tools tends to decrease the chip discharge ability due to a low friction at chip-rake face of tool. Thus, this study focused on the nickel-phosphorus (Ni-P)/abrasive particle composite films. Good mechanical properties such as wear resistance, corrosion resistance, and self-lubrication of the Ni-P/abrasive particle composite film can be obtained by changing the plating particle, particle size, or plating solution. In addition, the abrasive particles in the composite film should polish the chip surface such that the polished chips are easily broken. Thus, the composite film is expected to prevent chip snarling on the tapping tool and extends tool service life at high cutting speeds.

Based on the background mentioned above, the purposes of this thesis were to develop a tapping tool coated with a composite film composed of Ni-P/abrasive particles and investigate whether the tapping tool prevents chip snarling and increases tool service life even at high cutting speed conditions.

Chapter 2 explains the development and the tribological properties of Ni-P/abrasive particles composite film. The Ni-P/abrasive particles composite film was developed on a high-speed steel (HSS) disk using the electroless plating. Cubic boron nitride (cBN) and silicon carbide (SiC) were used as the abrasive particle because these particles have high hardness and these composite films are also known to process excellent mechanical properties. The cBN particles had a mean diameter of 10 μm, SiC particles of two different diameters, 5.0 μm and 1.0 μm, were used. These composite films were subjected to heat-treatment at 300 °C. The hardness and adhesion strength of the composite films and the friction coefficient under lubrication by emulsion cutting were investigated. For
comparison, these tests were conducted for a disk specimen with steam treatment (conventional treatment) or coated with TiCN film.

The analysis clarified that the hardness of the Ni–P film was about 9 GPa and higher than the steam treatment (Fig. 1 (a)), and the composite film had excellent peeling resistance (Fig. 1 (b)) and no film separation was observed. The Young’s modulus of Ni–P film was 230 GPa, which is similar to that of the HSS substrate (220 GPa). Therefore, it is considered that there was no delamination or peeling during scratch testing because the equivalent strain was produced when the contact load was applied. The friction coefficient for the composite films was greater than 0.15 and sliding velocities under emulsion-oil lubrication (0.05-0.25 m/s) that were higher than those of the other specimens, which was due to the ploughing by the abrasive particles in the composite film (Fig. 1 (c)). These results suggested that such composite films can be used as coating materials for tapping tools and may increase their service life without inducing chip snarling.

Chapter 3 demonstrated the development of tapping tools coated with the Ni–P/abrasive particle composite film and the cutting performance, such as the cutting resistance and the quality of the thread hole, of the tapping tool. A spiral-cut tapping tool (M6×1) was coated with the Ni–P/abrasive particle composite film, which is the same as the composite film introduced in chapter 2. The tapping test was conducted using a vertical machining center. The workpiece material was rolled structure steel (JIS SS400). The cutting speed was 10, 30, or 50 m/min. The lubrication was provided by emulsion cutting oil. The cutting torque and thrust force were measured using a dynamometer. In addition, to evaluate the quality of thread hole, the surface of thread hole was observed using SEM and the shapes of thread hole were tested using screw thread-limiting gauge.

The results showed that the tapping tool coated with the Ni–P/abrasive particle composite films satisfied the standard for thread gauge at high cutting speed condition. However, the Ni–P/cBN film caused the severe adhesion with plastic flow at the surface of thread hole at all cutting speed as shown in Fig. 2. Figure 3 shows the cutting resistance as a function of cutting speed. The cutting torque produced by the tapping tool coated with the Ni–P/cBN film (d = 10 μm) was the highest value in comparison with the other tapping tools. This suggested that the cBN particle (d = 10 μm) used was considerably large for the surface treatment of tapping tool. In contrast, the thrust force of the tapping tool coated with the Ni–P/abrasive particle composite films were lower than that of the others. Thus, these results suggested the optimal size of the particles used in the composite film was less than 5.0 μm, as an excessively rough tool surface may cause damage and decrease the dimensional accuracy of the thread hole.
In chapter 4, whether the tapping tool coated with Ni–P/abrasive particle composite film was able to prevent the chip snarling at high cutting speed and increase the tool service life was investigated. The tapping tests for SS400 were conducted at high cutting speeds. The chip geometry was evaluated and the relation between the chip curl diameter and chip snarling rate was clarified. Furthermore, the mean friction coefficient was estimated from the measured cutting torque and thrust force. The effect of the estimated mean friction coefficient on the prevention of the chip snarling was investigated.

The results demonstrated that the rate of chip snarling of the tapping tool coated with Ni–P/abrasive particle composite film was lower than that of other tapping tools. Particularly, the tapping tool coated with Ni–P/SiC film \((d = 1 \mu m)\) had a chip snarling rate of less than 5% at 50 m/min. The chip snarling rate tended to increase as the chip curl diameter increased as shown in Fig. 4. The rate of chip snarling exceeded 40% at a dimensionless chip curl diameter of approximately 1.0. The chip curl diameter decreased with increasing of the mean friction coefficient as shown in Fig. 5. The mean friction coefficient of the tapping tool coated with Ni–P/abrasive particle composite film was higher than that of other tapping tools. Additionally, the tool service life of tapping tool coated with Ni–P/ SiC film \((d = 1 \mu m)\) was 1.6 times greater than that of conventional tapping tool at 50 m/min without chip snarling as shown in Fig. 6 and Fig. 7.

Chapter 5 discussed the effect of the local friction coefficient at the sliding zone and secondary shear zone thickness on chip curl diameter. The local friction coefficient on the sliding zone and the secondary shear zone thickness were estimated using the sticking–sliding friction model. Additionally, the chip was padded with resin and the cross section of the padded chip was polished to survey the secondary shear zone. The cross section of the chip was observed using a reflection electron microscope and investigated whether the secondary zone exists or not.

The results indicated that the chip curl diameter decreased as the local friction coefficient at sliding zone increased as shown in Fig. 8. The local friction coefficient at the sliding zone of the tapping tool coated with the Ni–P/abrasive particle composite films was over 1.58 and higher than that of other tapping tools. The secondary shear zone was affected by the local friction coefficient at sliding zone; the secondary shear zone thickness increased with increase of the local friction coefficient as shown in Fig. 9. Furthermore, the secondary shear zone thickness observed using a reflection electron microscope was almost equivalent to the estimated value. According to these results, the chip curl diameter of the tapping tool coated with the Ni–P/abrasive particle composite films decreased due to the secondary shear zone thickness generated by the high local friction coefficient at the sliding zone at high cutting speed.
In chapter 6, the effect of workpiece material on chip snarling for tapping tool coated with Ni–P/abrasive particle composite film was investigated. The tapping test was conducted on the workpiece materials made from chrome molybdenum steel (JIS SCM440) and carbon steel (JIS S25C and S45C). The temperature at the primary shear zone was estimated to investigate the thermal effect on the chip curl diameter.

The results indicated that the rate of chip snarling increased as the dimensionless chip curl diameter. The dimensionless chip curl diameter of the tapping tool coated with Ni–P/SiC particle composite film was less than 0.9 for all workpiece materials and the rate of chip snarling of the tapping tool coated with Ni–P/SiC particle composite film was less than 10%. The secondary shear zone thickness increased with increase of the local friction coefficient at the sliding zone when the tapping tool coated with Ni–P/SiC particle composite film was used. Additionally, the chip curl diameter was affected by the cutting speed, i.e. temperature at the primary shear zone and decreased as the temperature decreased. The dimensionless chip curl diameter was less than 0.6 when the secondary shear zone thickness was at least 23 µm and the temperature at primary shear zone was lower than 495 K as shown in Fig. 10.

Chapter 7 describes conclusions, where the results of the thesis and main conclusions are summarized.

The tapping tool coated with Ni–P/abrasive particle composite film was developed and the chip snarling prevention and the tool service life extension was investigated in this thesis. As the results of the study, the tapping tool coated with Ni–P/SiC particle composite film prevented the chip snarling on the tapping tool at high cutting speed and increased the tool service life at 50 m/min.
論文審査結果の要旨

タップ工具への切りくずの巻付きは、ネジ穴加工における加工能率の向上、工具寿命の延伸を妨げる主要な要因となっている。本研究では、硬質粒子を表面に電着させた硬質粒子電着タップ工具を開発し、同タップ工具が切りくずの巻付きを抑制できること、工具寿命を向上できることを実験的に明らかにするとともに、工具・被削材料間の摩擦係数に基づいて切りくずの巻付き抑制機構を明らかにしたものである。本論文は、これらの研究成果についてまとめたものであり、全編7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、立方晶室化ホウ素粒子、炭化ケイ素粒子をそれぞれニッケルリンメキシにより電着させた硬質粒子電着被膜を作製し、これら被覆膜が耐硬度、基材との高い密着強度、切削油潤滑下において高摩擦を示すことを明らかにしている。これは、硬質粒子電着被膜のタップ工具への応用のための基盤的知見であり、有用な成果である。

第3章では、硬質粒子電着タップ工具を開発し、一般構造用圧延鋼材SS400を被削材料とするネジ穴加工実験により、硬質粒子電着タップ工具が高速加工条件においても折損防止効果を有すること、規格内のネジ穴形成精度を示すことを明らかにしている。これは、硬質粒子電着タップによるネジ穴加工への有用性を示す重要な成果である。

第4章では、硬質粒子電着タップ工具が、従来の5倍の高速加工条件において切りくずの巻付き抑制効果を有することと、従来のタップ工具の2-6倍の工具寿命を示すことを実験的に明らかにしている。これは、硬質粒子電着タップによる高速ネジ穴加工が可能であることを示す重要な知見である。

第5章では、工具すき間と被削材間における摩擦係数の推定方法を提案するとともに、摩擦係数と切りくずのカール径の関係に基づいて、硬質粒子電着タップ工具による切りくずの巻付き抑制機構を明らかにしている。これは、切りくず巻付き抑制効果を有するタップ工具の設計指針を示すものであり、重要かつ有用な知見である。

第6章は、4種類の炭素鋼材料に対してネジ穴加工実験を行い、硬質粒子電着タップがいずれの被削材に対しても、従来の5倍の高速加工条件において、切りくずの巻付き抑制効果を有することを明らかにしている。これは、硬質粒子電着タップの実用向けの有益な成果である。

第7章は結論である。

以上要するに本論文は、硬質粒子電着被膜を有するタップ工具を開発し、同タップ工具が高速加工条件において切りくずの巻付きを抑制できること、工具寿命を向上できることを実験的に明らかにするとともに、切りくずの巻付き抑制機構を明らかにしたものであり、機械システムデザイン工学ならびにトライポロジー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。