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論 文 内 容 要 旨

Poor machinability of hard-to-machine materials limits their applications in aircraft industries. From the viewpoint of reductions of cost, it needs a more efficient and productive way to produce these materials. However, the grinding process is brittle material with small size grain, putting it at a disadvantage for large-variety production. In order to improve the grinding ability, one novel hybrid and two multi-filed assisted grinding technologies are proposed and experimental text with hard-to-machine materials in this study. The multi-field assisted machining is combined ultrasonic vibration, electrochemical and plasma electrolytic oxidation into grinding, meanwhile, named them as ultrasonic vibration assisted grinding, ultrasonic assisted electrochemical grinding and ultrasonic assisted plasma oxidation grinding, respectively.

First, the ultrasonic assisted grinding (UAG) apparatus was designed and constructed. An experimental apparatus was established by installing a commercially available ultrasonic spindle onto a commercially available NC grinder through a 3-components piezoelectric dynamometer. The dynamometer was located below the spindle and used for the measurement of grinding forces. In experiments, the workpiece specimen was fixed on a work-holder under which a Z-stage is located for determining the depth of cut. The working surface condition of abrasive tool is one of important issues in grinding process. This article discusses the effects of the ultrasonic vibration on the working surface condition involving chips adhesion and abrasive grains wear during UAG of Inconel 718 with an electroplated cBN grinding wheel as the abrasive tool. In this study, scanning electron microscopic (SEM) observations were performed on the wheel working surface before and after grinding at different vibration amplitudes and the SEM images were filtered, extracted and binarized by using Image-Pro Plus to evaluate the wheel working surface condition. The obtained results demonstrated that (1) the wear of grinding wheel are dominantly attributed to chips adhesion, grains releasing and grains fracture, (2) both the percentage of chips adhesion area and the size of chips adhered tend to decrease as the vibration amplitude increases; in contrast, the effect of ultrasonic vibration on the number of chips adhesion are not noticeable, (3) the percentage of the number of grains released/fractured decreases as the vibration amplitude rises; e.g., the percentage in UAG at vibration amplitude of $A_{p\text{-}p}$=9.4μm was decreased by 40% compared to that in conventional grinding (CG), (4) higher distribution density of effective cutting edges can be achieved under larger vibration amplitude, and the mean area of effective cutting edges in UAG is smaller than that in CG, demonstrating that the ultrasonication enhances the grinding wheel sharpness.

In order to improve the grindability of Ti–6Al–4V, a multi-fild material removal process was proposed in this study. This process was a combination of ultrasonic assisted grinding (UAG) and electrochemical grinding (ECG); hereafter named as ultrasonic assisted electrochemical grinding (UECG). In order to confirm the feasibility of the proposed technique, an experimental setup was constructed and the fundamental machining characteristics of UECG in the grinding of Ti–6Al–4V were experimentally investigated. The results obtained from the investigation summarized as follows: (1) The normal and tangential grinding forces in UECG were smaller than those in conventional grinding (CG) by 60% and 65%, respectively; (2) The work-surface roughness, Ra, both in ECG and UECG decreased with the increasing electrolytic voltage, U_I, and surface damage, such as plastic deformation and cracks, (which often occur in CG) were not observed in UECG; (3) The wheel radius wear in UECG was considerably smaller than that in ECG when U_I < 10 V. The wheel wear in CG was predominantly attributed to the grain drop out, whereas in ECG and UECG the working lives of the wheels were predominantly affected by the chip adhesion and the grain fracture; (4) A 78 nm thick titanium dioxide (TiO_2) layer was generated on the work-surface at U_I = 20 V, and thus the Vickers micro-hardness of work-surface in UECG was lower than that in CG/UAG by 15%; (5) The weight percentages of oxygen elements on chips and work surfaces increased as the U_I increased in ECG and the ultrasonic treatment further enhanced the percentages of oxygen.

Then, the ultrasonic assisted plasma oxidation grinding (UPOG) was investigated. Before material removing, plasma oxidation are important issues in ultrasonic assisted plasma oxidation grinding. In order to investigate grinding parameters to achieve high product quality and productivity, the relation between ultrasonic vibration and plasma oxidation is studied. Effects of grinding parameters (workpiece rotational speed, wheel feed rate, wheel rotational speed, ultrasonic vibration amplitude, and the oscillation frequency), on plasma oxidation are measured. The experiment results show once the plasma voltage was applied, the hardness became decreased. However, when the plasma voltage U_I was beyond 100 V, the plasma discharge intensity became higher locally, which resulted in the formation of melt-quenched, high-temperature oxides on the work surface.

To deeply investigate the material removal mechanism in UPOG of Ti-6Al-4V, the UPOG tests were performed on Ti-6Al-4V. The obtained results evidence that: The grinding forces decreased as the plasma voltage U_I and rotational speed n_g increased. The actual removal depth increased with the increase in input voltage. However, the benefit of the ultrasonication to the grinding efficiency would get smaller when the rotational speed has been set at a larger value. The roughness Ra both in POG and in UPOG decreased with the increasing of U_I and n_g; the roughness Ra in UPOG was smaller than that in POG regardless of the process parameters. The UPOG of Inconel 718 was also very effective with high voltage.

The last part of this study is to extend the method on drilling with UPOG so as to open a door to potential industrial applications. The results show that material removal rate in UPOG is deeper than that CG, meaning that material removal is easily achieved in UPOG; high accuracy can be achieved by UPOG.

All in all, this study confirms that UPOG is a highly effective processing method for hard-to-machine material. The technology has the potential to being further extend to other materials.

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論文審査結果要旨

本論文は、マルチフィールド（超音波、電気化学、プラズマ）を援用して、航空難加工材料を高能率で研削する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。航空難加工材料は、高強度、耐熱性、耐食性に優れた特性を持つ反面、機械加工が難しい難削材として知られている。特に低い熱伝導率や高い粘着性と靭性のため、従来の研削加工では砥石の目詰まりや摩耗が激しく、作業寿命が短い。これによって加工能率が低く、加工コストが高いという課題がある。そこで本論文では、電気化学またはプラズマの作用によって脆くて柔らかい酸化層が形成される点、また砥石に超音波振動を付与すると酸化現象がより促進される特徴に着目し、電気化学またはプラズマ／超音波といったマルチフィールドを援用した研削法を提案した。第 2 章では、Inconel 718 の超音波援用研削を行い、加工能率の向上と砥石摩耗の軽減に対する超音波の援用効果を定量的に確認している。第 3 章、第 4 章では、それぞれ Ti-6Al-4V の超音波／電気化学と超音波／プラズマの複合援用研削について検討している。電気化学やプラズマを作用させ、酸化層の生成現象を調べた上で、加工条件が研削抵抗や面粗さ及び砥石摩耗などに及ぼす影響を体系的に検討し、加工条件の最適化を図っている。その結果、超音波／プラズマ複合援用で研削抵抗が最も低減できる（本実験条件の範囲内で、従来研削に対して法線抵抗が約 60%、接線抵抗が約 70%減少）ことを明らかにしている。第 5 章では超音波／プラズマ複合援用研削による Ti-6Al-4V の穴あけについて検討している。従来研削および超音波援用研削では加工途中で砥石が折損してしまったのに対し、超音波／プラズマ複合援用研削では研削抵抗が大幅に低減して砥石作業寿命が大きく伸びたため、貫通穴が得られることを明らかにしている。第 6 章では本研究で得た結果をまとめ、今後の課題を提起している。

本論文はこれまでにない難削材の新しい研削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、査読付国際学術論文 4 編、国際会議発表 5 件、国内学会発表 4 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。