The Present Situation and Development of Small Holes Machining Technology

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Abstract: It is one of the concerns problems in machinery manufacturing industry of the small holes machining and people has been committed to improve the machining quality, efficiency of the small holes and reduce the machining cost, realized the machining of the small holes on the difficulty-to-machining material. There are some kinds of technology for the small holes machining. For the questions in the small holes machining, based on the up to date development of the small holes machining technology, the application and research current situation of the Mechanical Machining and the Non-traditional Machining such as Laser Machining, Electrochemical machining, Ultrasonic Machining, Electric Discharge Machining and so on in small holes are summarized. The development prospects of various complex machining methods for small deep hole machining in the future are also described in the paper.

1. Introduction

With the rapid development of science and technology, the application of refractory materials in the field of modern manufacturing industry is more and more extensive, especially in aerospace, automobile, mold and other manufacturing fields, its outstanding material properties, such as high strength, heat resistance, wear resistance, corrosion resistance and so on to improve product performance has achieved great economic benefits. In many parts processing, deep holes and micro deep holes processing have always been concerned widely in machinery manufacturing industry [1].

Micro-deep holes exist in all areas of life, such as aerospace, military production, oil cylinder holes, shaft axial oil holes, hydraulic valve holes, nozzles, molds, medical equipment, watches and other civilian parts [2]. Because of the cooling of the cutting tools in the micro-deep hole, chip problem couldn’t be resolved timely, the problems of broken knives and other appear frequently, and for some difficulty to cutting materials, traditional processing methods can’t be machined easily. Combined with the recent situation of micro-deep holes processing, the current stage of micro-deep holes
processing methods were summarized in this paper. According to the different processing principle, small holes processing methods can be divided into two main categories: machining methods and non-traditional machining methods. Traditional machining methods mainly include drilling, special processing methods mainly include laser processing, ultrasonic machining, electrolytic processing, EDM, electron beam processing, and so on [3].

2. Traditional Machining Methods for Micro-deep Holes

The earliest application of drilling technology in small holes processing is the watch manufacturing industry. Drilling which has some characteristics such as high production efficiency, unlimited in material conductivity, is superior processing in economic, precision, efficiency, and for large holes, low ratio of depth to diameter and precision holes, ordinary drilling processing can generally meet the processing requirements [3]. However, there are many technical difficulties in drilling micro-deep hole, which is mainly improved from the aspects of processing machinery, technological means and cutting tools. In processing machinery aspect, with high-speed motor, motorized spindle and other equipment appearing, it made the spindle speed of drilling machine continuously improve, such as Switzerland Fisher Company and France forest-line, the motorized spindle has a spindle speed of up to 180000r/min [4]; new motorized spindle components supplemented more advanced feed mechanisms, which can produce smaller, higher efficiency micro-deep hole drilling equipment. Air bearing, magnetic bearings and other technologies make the spindle rotary precision further improved, such as Japan NSK Company produced precision spindle with rotary precision 1μm. In the processing technology aspect, in order to prevent the bit breaking and improve drilling accuracy, the drill sleeve or guide sleeve was used and the drilling process in division. In order to improve the stiffness of bit and chip removal effect, the ultrasonic vibration is introduced into the drilling, the traditional drilling and ultrasonic vibration are combined, which showed that the surface roughness of the machined hole is reduced and the roundness is obviously increased[5-7]; In the tool aspect, the new tool material, the new tool geometry structure, the coating technology and so on has made the bit performance and the service life improved and the drill bit diameter also is getting smaller. The Japanese good friend Electrician company introduced a kind of MDSS-type carbide drills with a minimum diameter of φ30μm and a maximum machining depth of 60μm, and the company produces another hard Alloy drill for φ0.2mm, with a depth ratio of up to ten and cutting speed 40-300mm/min[8,9].

3. Non-traditional Methods for Methods for Micro-deep Holes

Non-traditional processing technology refers to the use of sound energy, electrical energy, thermal energy, light, chemical energy, electrical energy, or a combination of various energies to achieve material removal processing methods, such as laser processing, electrolytic processing, ultrasonic machining, Electrical Discharge Machining, electron beam processing and so on.

3.1 Laser Machining of Micro-deep Holes.

The focusing system is used in the Laser Machining, when light energy is through the focusing system, Excitation optical processing of small holes is the use of light energy through the focusing system, a high energy density is formed on the workpiece and it occurs instantaneous melting, gasification, melting and gasification of explosive ejected and the micro-deep holes are formed at last [10].
Compared with traditional machining methods, it has high processing speed, high efficiency, small heat affected zone and so on for the laser machining, and it is suitable for the processing of all kinds of materials, and the smallest diameter can be reached to 4-5μm, the depth diameter ratio up to 10 above. The DML Series Laser Machining Center, manufactured by DMG Company of Germany, with output power up to 10-20kw, surface roughness up to Ra 1μm, the maximum material removal rate up to 25mm3/min machined the minimum holes with diameter of 5μm, depth of 20mm [11], but the hole roughness, roundness ratio is poor and it is easy to form trumpet, the hole accuracy is generally lower than IT8 level. As the cost of the laser equipment is expensive, the application is limited [12, 13].

At present, it is researched mainly on two aspects at home and abroad to improve the laser processing performance, and reduce the eliminates micro-cracks, casting layer.

(1) Shorten laser pulse width and increased peak power. With the advent of femtosecond laser, the laser processing technology achieve breakthroughs, and the thickness of the casting layer can generally be controlled in the 0.02-0.05mm and pulse width is shortened to 3fs, The instantaneous high energy density deposition will change the absorption and motion of electrons, making femtosecond laser processing a non-hot melt process cause with ultra-high accuracy, high spatial resolution and ultra-high universality. 100μm Micro-holes were machined on the 1mm stainless steel plate through, high-energy-density femtosecond lasers of the German Hannover Laser Center in Fig.1 [14, 15].

(2) Laser combined processing. It mainly includes injection gas assisted laser machining, underwater laser machining, chemical assisted laser machining, ultrasonic assisted laser machining, water guide laser machining, and so on [16], and the processing quality, reduce micro-cracks, cast layer and heat affected zone is improved significantly. The recrystallization of micro-cooling holes in laser machining was controlled and removed accurately and the thickness of the recrystallization is reduced to 5μm by the optimizing technology parameters of the 150fs high energy density laser by Xi'an Jiaotong University research group, there were machined micro-holes without cast layers in Fig.2, where figure A was the overall profile and figure B was the section local profile [17].

3.2. Electrochemical Machining of Micro-deep Holes.

Electrochemical Machining (ECM) is a non-traditional method based on anodic ion dissolution principle with a high machining speed, good surface quality, wide processing range, no macro-mechanical cutting force, no loss of cathode and so on, and it had developed to Copy-type Electrochemical Machining, Pulse Electrochemical Machining, CNC Electrochemical Machining, Electrochemical Micro-Machining and Electrochemical Composite Machining, and it has become a key technology in aerospace manufacturing field, which is widely used in the production of engine blades and other parts in weapons, automobiles, medical equipment, electronics, molds and so on [10].
However, because of the interaction of electrochemical, electric field and flow field in the gap, it was difficult to ensure the machining stability and the processing precision. Meanwhile, the Electrochemical Machining equipment needed the anti-corrosion requirements, and electrochemical products also needed to be treated properly, which limited the application.

The electrochemical machining technology has been studied extensively at home and abroad. The rule of pressure distribution in the gap in STEM is calculated by Zhu Di research group in Nanjing University of Aeronautics and Astronautics and the results showed that the expansion electrolyte channel is the main cause of the hole phenomenon in the machining area, and the translation electrode is used in the ECM, which can transfer the hole region during the process, it eliminate the protruding from machined workpiece surface and get good processing stability [18,19]. Wang Wei et al. analyzed the flow field in the distribution cavity of the tube electrode, and the results showed that the reduction of the number and inner diameter of the cathode and the increasing the total drag coefficient both can make the flow field evenly in the cavity, and the wedge-shaped cathode can effectively improve the flow field distribution in the machining gap [20]. Fang Xiaolong et al. proposed positive potential difference auxiliary anode tube electrode processing method and the distribution of the electric field in the machining gap of the tube electrode is improved, the stray corrosion of the hole is weakened, the sensitivity of the tube electrode to the feed depth is inhibited, the electrochemical machining accuracy is improved, and the method of the pulsating flow field electrolysis is proposed. The study shows that the suitable pulsating flow field can improve the stability and machining precision of micro deep hole processing, and increase the depth of micro deep hole processing [16].

The Nickel-based super alloy was machined by ECM using NaCl mixed electrolyte with 1%HCl by Indian Polytechnic University, the regularity of machining diameter varied with the machining depth was analyzed, and the prediction model of machining gap is established to machining bamboo cooling hole by staged changing the voltage and feed rate [21]. Poland Warsaw University of technology carried out the pulsed electrochemical machining, the processing gap in the electrolytic products can be fully discharged during the pulse intermittent time and obtained a stable machining process, but it reduced the efficiency of ECM [22]. British Manchester University S. Hinduja et al. summarized the common hole defects in the processing of micro-deep holes by bipolar current electrodes, and analyzes the main factors affecting the diameter and taper of the machining voltage, feed rate, electrolyte pressure and electrolyte concentration through factorial design, and the mathematic model of machining bamboo cooling holes using feeding tube electrode was established [23].

3.3 Ultrasonic Machining of Micro-deep Holes

Ultrasonic Machining is the use of ultrasonic vibration tools in the liquid medium with abrasives or in dry abrasives to produce abrasive impact, grinding, hydraulic impact and the resulting cavitation action to remove material, or vibrate the tool or workpiece in a certain direction to realize vibration processing, or to make the workpiece together using ultrasonic vibration [10].

A great deal of research work has been done around the ultrasonic machining technology at home and abroad. The feasibility study of rotary ultrasonic machining Carbon Fiber Reinforced Plastic (CFRP) was carried out in Beihang University. The test results showed that the material removal rate, machining precision and surface quality is improved, and the tool loss is reduced compared with the drilling process [24]. The Kansas State University in the United States has developed rotary ultrasonic machining research on ceramics, ceramic matrix composites (CMC), Carbon fiber reinforced (CFRP),
CFRP/Ti, the calculation method of ceramic material removal rate model machined by rotary ultrasonic machining was proposed, and the mathematical model of cutting force was established, The change of power consumption of rotary ultrasonic machining with processing factors was analyzed for CFRP [25]. Dalian University of Technology had carried out experimental research on rotary ultrasonic machining of Potassium Dihydrogen Phosphates (KDP) and obtained better surface quality by the rotary ultrasonic machining using the tool of face chamfering [26]. Tianjin University used the ultrasonic signal through the electromagnetic conversion method to drive the tool movement and machined the hard and brittle materials and, ultrasonic vibration grinding was applied to machine the engineering ceramic small holes, and the experimental research was carried out to study the impacted factors on the processing efficiency and processing quality [27]. Harbin Institute of Technology machined diameter φ13μm micro-hole on the silicon wafer using a constant-speed feed, and developed a new type of 4 Shaft ultrasonic assisted EDM devices, and machined the less than φ0.2mm, greater than 15 depth diameter ratio holes on the titanium alloy [28]. Nanjing University of Aeronautics and Astronautics combined with the ultrasonic machining technology, EDM technology and electrochemical machining technology, and formed into ultrasonic assisted EDM technology and ultrasonic assisted electrochemical machining technology and the results showed that the vibration on the workpiece is advantageous to the circulation of working fluid during EDM, and the pulse utilization of micro-EDM and the depth diameter ratio of micro-hole are improved[29], the hard and brittle metal materials were machined by the ultrasonic assisted electrochemical machining and micromachining, and It is shown that the compound processing method can improve the machining speed, forming precision and surface quality, and it is better than single ultrasonic machining and electrolytic machining process[30].

3.4 Electrical Discharge Machining of Micro-deep Holes

Electrical Discharge Machining (EDM) principle is based on the pulse of spark discharge phenomenon between the tool and workpiece to remove excess metal.it is the use of electrical energy, heat energy to remove metal in EDM, and the hot cast layer, the heat influence zone was formed on the processing surface, which affected service life of the part. The surface quality and the precision of the holes was poor machined by the electric energy and thermal energy, and had a certain taper. It is not easy to manufacture the electrode and easily deformed and dissipated with low efficiency, trouble in chip and scattering in micro-deep holes by EDM, which is the main problem affecting the wide application [10].

The small holes machining is an application of spark-erosion drilling. As the tool electrode section area is small, it is easy to deform, hard to dissipate heat, chip and the pulling arc caused in the processing area hinders the normal EDM. As the electrode loss is big, and the electrode is too long to cause short circuit, so the depth of spark-erosion drilling is limited, and the depth diameter radio is about 20[31].

For the shortcomings of spark-erosion drilling, the dual-hole tubular electrode and edge cutting electrode were used to improve the efficiency, reduce the taper and the electrode dissipation in the micro-EDM small deep hole processing, with the inverted workpiece the processing depth and processing stability was improved [32]. The micro-deep holes EDM machine tools to machine the 2000mm small holes was developed by Beijing Yi-Power Processing Institute and improved the processing efficiency and processing accuracy [33]. The technology indicators of the domestic
production of CNC high-speed EDM for micro-deep holes have reached the international advanced level, and the depth to diameter ratio had exceeded the 1000:1[34].

4. Development Trends of Micro-deep Hole Processing Technology

With the development of science and technology, the emergence of new materials, the future of micro-deep hole precision machining is bound to be no longer a single processing method to complete, the complex processing method will inevitably become the development trend, and the combined processing methods mainly include ultrasonic vibration drilling, electrochemical mechanical combined processing, electrochemical EDM combined processing, electrochemical laser combined processing and ultrasonic electrochemical combined processing technology and so on.

4.1 Ultrasonic Vibration Drilling of Micro-deep Holes

The ultrasonic vibration is applied on the bit, so that the cutting edge of the bit and the workpiece was periodically separated, and the cutting force is periodic, meanwhile, the rigidity of the bit is strengthened. The vibration of the drill mainly contained axial vibration, torsional rotation vibration and axial torsional composite vibration as shown in Fig.3, the mode of action between the bit and the workpiece was changed using of high-frequency ultrasonic vibration in the vibration drilling, and the state of cutting is changed from continuous cutting to intermittent cutting, which improved the performance of discharging chip and the cooling and heat dissipation conditions have also been improved. the formation of the pulse torque greatly make the friction coefficient reduced between the bit and workpiece, bit and chip, which effectively reduced the drilling force and improved the service life of the bit and the quality and efficiency of the machined surface. The dynamics of the machining process, the mechanism of chip breaking, the drilling force about the ultrasonic vibration drilling were studied to improve the machining precision and surface quality [35].

Professor Zhang Deyuan in Beihang University, Professor Zhaopo in Henan Institute of Technology had long-term committed to the development of ultrasonic-assisted drilling devices and systems, and had designed a variety of shape thickness workpiece ultrasonic vibration table to achieve ultrasonic-assisted drilling Machining [35]. the comparison of ultrasonic vibration cutting with traditional cutting for materials were carried out by VARUN et al., and the results showed that the former had lower cutting force and tool wear, and its surface quality can reach nanometer level[36]. The depth diameter ratio greater than 10 holes were machined successfully on nickel-based cemented carbide with ultrasonic vibration drilling by GHLANI et al., and lower spindle speed can reduce axial force and surface roughness[37].
4.2 Electrochemical-mechanical Combined Machining of Micro-deep Holes

Electrochemical-mechanical Combined Machining is mainly the use of mechanical action to remove the passivation film produced in ECM and make the ECM to continue, it is a combined processing technology which is main ECM process with supplemented mechanical process, the processing principles was shown in Fig. 4 [10].

A lot of research had been done on the basic research and application development of Electrochemical-mechanical Combined Machining in China. A series of research on electrochemical grinding was carried out in Nanjing University of Aeronautics and Astronautics and Changzhou Institute of Technology. For the overall impeller blade surface finishing problems, the machining mechanism research on five-axis CNC electrochemical grinding was carried out and the polishing efficiency of the overall impeller was improved to 12 times [38]. The preprocessed micro-deep holes was polishing by the electrochemical grinding Professor Zhu Di et al. and obtained the best technological parameters, as shown in Fig.5, which can meet the requirements of fuel nozzle[39].

4.3 Electrochemical EDM Combined Machining of Micro-deep Holes

Electrochemical EDM Combined Machining is to make full use of the high precision of EDM and the better surface quality of ECM. In the same processing station, under different tool electrode conditions, the EDM is the firstly done, and then the ECM is done to remove the production of the casting layer, the machining principles was shown in Fig.6[10].

The advantages of EDM and ECM are integrated on the electrochemical EDM combined machining technology, and the disadvantages are also made up. It is suitable for difficult-to-machine
metal materials and is effective technology for the micro-deep holes processing, but there is the casting layer on the processing surface, which affected the performance of the part. ECM is based on the electrochemical anodic dissolution principle to remove the metal material in the ion form with good surface quality, high processing efficiency, no loss of the tool, no cutting stress and the casting layer. However, the precision of ECM is difficult to achieve high-precision, and the EDM has a high precision, the two processing technology combined to avoid weaknesses and obtain high processing accuracy and surface quality [40].

The experiments of micro-deep holes machined by the Electrochemical EDM Combined Machining on the heat-resisting alloy, titanium alloy and alloy steel and so on materials were carried in University of Edinburgh and were applied on the micro-deep holes processing on the thin-walled heat-resisting alloy of the aircraft engine [41]. Korea Yousei University presented the research of single end insulated electrode for ultrasonic electrochemical and EDM compound machining, and improved the machining depth [42]. Non-conductive super hard materials processing was explored in Harbin Institute of Technology and the using of physical inflatable method and tool electrode ultrasonic vibration can improve the efficiency of electrochemical assisted EDM[43].

4.4 Electrochemical Laser Combined Processing of Micro-deep Holes

Electrolyte Jet - Laser combined processing is proposed based on "water jet guided laser processing" and "Electrolytic jet hole processing" and the processing principles was shown in Fig.7 [10], the workpiece material is removed in the electrolyte jet by electrochemical dissolution, and the laser beam removes the material in the form of total reflection under the guidance of the electrolyte jet, and the local temperature of the electrolyte is elevated, the machining efficiency is increased, and the localization of the electrolyte jet processing is strengthened. the taper of the machined holes was reduced with the high efficiency machining of laser beam, which also increased the depth diameter ratio, and removed the defects such as the casting layer, residual stress and micro-crack caused by the laser processing. The combination of two processing methods not only keeps the surface quality of the electrolyte jet processing well, but also makes full use of the high efficiency characteristics of the laser processing, which making up the deficiencies of the respective processing.

Professor P. T. Pajak has studied the technology of laser-assisted electrochemical jet machining in Glasgow Caledonian University, and the results showed that the precision and efficiency of electrochemical machining were greatly improved, and the surface processing quality was improved, and there were no casting layer, residual stress and micro-cracks [44].
The surface quality and processing efficiency of the holes machined by electrochemical laser combined processing was studied in Nanjing University of Aeronautics and Astronautics, and the results showed that the electrochemical laser combined processing can effectively remove the casting layer and spot produced by laser processing, and there were no heat-affected zone on the surface, but the processing efficiency is decreased to 30% [45]. There were the machined holes in Fig.8, where the figure A was the entrance of the holes and the figure B was the exit of the holes.

4.5 Ultrasonic Electrochemical Combined Processing of Micro-deep Holes

Ultrasonic Electrochemical Combined Processing is the compound processing technology combined the electrochemical machining and ultrasonic machining. Any metal materials can be machined by the ECM with high processing speed, but it is easy to generate the passivation film to prevent the ECM. Ultrasonic machining has high precision, good surface quality, but the processing efficiency of metal is very low. By combining the two processing methods, ultrasonic high-frequency vibration and cavitation can effectively remove the passivation film produced in ECM, and the high frequency vibration and cavitation of ultrasonic wave can help to update the electrolyte and discharge the electrochemical product, and ensure the electrochemical machining to continue. By adding micro-abrasive in electrolyte, the machined surface was grinded by the abrasive, which not only improved machining speed, but also improved the machined surface quality. In the process of composite processing, the cathode moved to the workpiece at a certain feed speed with ultrasonic vibration, the passivation film on the surface was broken with the reaction of ultrasonic shock, cavitation or abrasive grinding action, and the anode surface continues to activate, and then dissolved. In this way, the workpiece anode surface has been passivation, activated alternating state, which improved the electrochemical processing speed. The processing principle was shown in Fig.9 [45].

Some research on the ultrasonic machining and electrochemical combined machining was carried out. A. Ruszaj studied on the complex textured surfaces by the electrochemical precision machining and analyzed the phenomena between the tool and workpiece in Polish Institute of Advanced Manufacturing Technology, in order to obtain the surface roughness of the Ra<100nm, the experiments were carried by pulsed electrochemical machining(PECM), ultrasonic electrochemical combined machining(USPECM) and ultrasonic electrochemical combined machining with abrasive
power in the electrolyte respectively, and the results showed that the surface quality machined by ultrasonic electrochemical combined machining was better than that by pulsed electrochemical machining, and the surface quality machined by the ultrasonic electrochemical combined machining with abrasive powder was the best[46]. The fluid flow in the ultrasonic-assisted electrochemical machining gap was analyzed using the theory of computational fluid mechanics by S. Skoczypiec, and the ultrasonic vibration made the cathode had an additional velocity. The unsteady turbulent flow between the poles was analyzed by the CFD, the results showed that the ultrasonic vibration can change the value of the pressure, velocity and strength of the region, and pointed out that the strength of the cavitation had an important effect on the dissolution state, and the strength of the cavitation was determined by the amplitude, so it was advantageous to reduce the polarization of the electrodes with the suitable amplitude. Through the comparison experiments of ultrasonic electrochemical combined machining and electrochemical machining, it was proved indirectly that ultrasonic vibration can reduce the electrode polarization and change the condition of the electrochemical solution and if the amplitude parameter was optimized, the polarization of the electrode is reduced [47].

Some corresponding researches on ultrasonic electrochemical combined processing technology have also been carried out at home. Professor Yunai Zhang in Nanjing University of Aeronautics and Professor Zhu Yongwei in Yangzhou University discussed the machining mechanism and technology advantages about ultrasonic electrochemical combined processing and a series experiments of ultrasonic electrochemical combined micromachining were carried out using different cross-section micro-tool cathode[48,49]. The basic experiments had initially confirmed that the feasibility and advantages of this composite technology. There were the micro-components machined by the device in Fig.10. The research on the micro-deep holes machined by rotary combined ultrasonic electrochemical processing by Professor Kang Min et al. in Nanjing Agricultural University. The rotary combined ultrasonic electrochemical machining device was designed with inner sprayed electrolyte. The processing flow field, the electric field was simulated and processing mechanism was analyzed. The compared experiments between rotary combined ultrasonic electrochemical machining (RCUECM) and the rotary electrochemical machining (RECM) of micro-deep holes were carried out and the results showed that it had more technology advantages in RCUECM. There were the machined micro-deep holes as shown in Fig.11, the hole in Fig. A was machined by RCUECM and the hole in Fig. B was machined by RECM respectively. The results showed that with the vibration of the cathode in RCUECM, the electrolyte is easier to update and the produce is easier to discharge, so the dissolve velocity of the anode is greater and the surface roughness is higher [50-53].
5. Conclusions

With the development of science and technology and the emergence of new materials, new requirements are put forward on the processing method, and the precision machining of micro-deep holes is no longer a single processing method to complete in future and the complex processing methods will inevitably become the development trend. The current machining situation of micro-deep holes is summarized in this paper, and the basic principle and research trends of each machining method are described from the traditional machining and non-traditional machining. According to the shortcomings of these single machining methods, the ultrasonic vibration and electrochemical machining is complex to various types of processing methods, the formed composite processing technology, helped each other, will be further developed and applied in the manufacturing industry in the future.

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