2017 WJTA-IMCA Conference and Expo
October 25-27, 2017 ● New Orleans, Louisiana

Paper

INTRODUCTION AND ANALYSIS OF THE ULTRAHIGH PRESSURE WATER JET CUTTING MULTIFUCTIONAL APPLICATION

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ABSTRACT

The aerospace industry bring a new development for ultrahigh pressure water jet cutting technology, such as large scale curved composite components cutting process engineering application, large scale impeller rough cutting, special precise cutting, composite materials to milling, drill, polishing and so on. As National Advanced Technology Support Project of China for an opportunity, the author developed 500MPa ultrahigh pressure water cutting equipment for super large composite wing and a multifunction water jetting CNC center. This paper introduce the ultrahigh pressure water jet multifunctional technical features about these two equipments involved, and combine with the foreign development situation. The technical modules, parameter matching technology, process method and experiment result are analyzed to realizing the highly-difficult water jet cutting, milling and other applications.

1. MARKET REQUIREMENT OF HIGH END ULTRAHIGH PRESSURE WATER CUTTING

In China, technology and equipment development of ultrahigh pressure water cutting have been a full twenty years. The first water cutting machine developed by author is 250MPa of pressure, 2.5L/min of flow. And the current main water cutting products which use ultrahigh pressure intensifier or reciprocating pump are 400MPa of pressure, 3L/min of flow [1]. So China has become the largest manufacturing base and market of water cutting products. However, from international water jetting technology conference, we can clearly find technology gap between China and International developed countries. They are ultrahigh pressure creative design ability, research & development capability of large special equipment, and intelligent application level. Take the most advanced technology as example, American Flow Company has developed several generations of five-axis water cutting heads, and made water cutting head from five-axis precision control to identify regulation [2]. These technologies have become the technical targets of peer companies.

The technology gap between home and abroad originated in market. Chinese water cutting technologies are focused on stone, glass and other low-end materials cutting. So it is necessary to make cross-developing technology research facing high-end market requirements. As a contrast, water cutting technology of United States originated in high-end aviation cutting applications. Because of technology development continuity, it can easily adapt to the target of new application.

There is no doubt that the aviation market requirements have greatly driven the development of ultrahigh pressure water cutting technology. Only compared Boeing 787 with 767 aircraft [3], material structure has been a great factor difference to achieve clean, quiet and efficient demands. Material structure of Boeing 787 consists of 50% composite material, 23% aluminum, 15% titanium steel, 6% steel, and 6% other materials. Furthermore, the ratio of composite material in Boeing 767 has reached 77%. Composite material, titanium steel and aluminum material has become the main processing target of ultrahigh pressure water cutting application. In addition, as for nickel chromium iron alloy and other steels, tool materials, plastic materials and laboratory testing materials, ultrahigh pressure water cutting process has shown superior performance. That is, water cutting will be extended to almost all commercial applications of aircraft manufacturing. It has been paid more attention and irreplaceable because of the composite materials processing difficulty.

Water cutting processing has many advantages [4]. It can be suitable and used for different materials processing and multifunction processing. It does not produce any thermal effect during processing. Because of water jetting force limit, it does not make any processing deformation of material. And it also does not make composite material produce delamination, splitting, edge scratches or other integrity problems. For general application, it does not processing any more after water cutting. And it can reduce tools and fixtures. Water cutting processing has been seem as clean, green, no dust, high efficient and potential. The non selectivity of water cutting materials cannot be achieved by any machining process. Therefore,

the range of water cutting application is more extensive. Moreover, due to the small volume of water cutting head and small water flow of micro water jetting, it can produce small motion inertia and reaction force. So it is easily to realize robot automatic operation. Therefore, it is beneficial to improve cutting speed and precision, simplify procedures, maintain easily and safety for operator. Of course, the outstanding shortcomings of water cutting are noise and abrasive costs.

2. LEVEL AND SYMBOL OF ULTRAHIGH PRSSURE WATER CUTTING

It is an important demand of aviation industry to processing large scale surface composite wing, tail and skin [5]. Because mechanical machining to composite materials will produce delamination, deformation and splitting, Boeing Company has made ultrahigh pressure water cutting with five-axis machine tool as a standard process. Therefore, large specialized water cutting machine tool has developed.

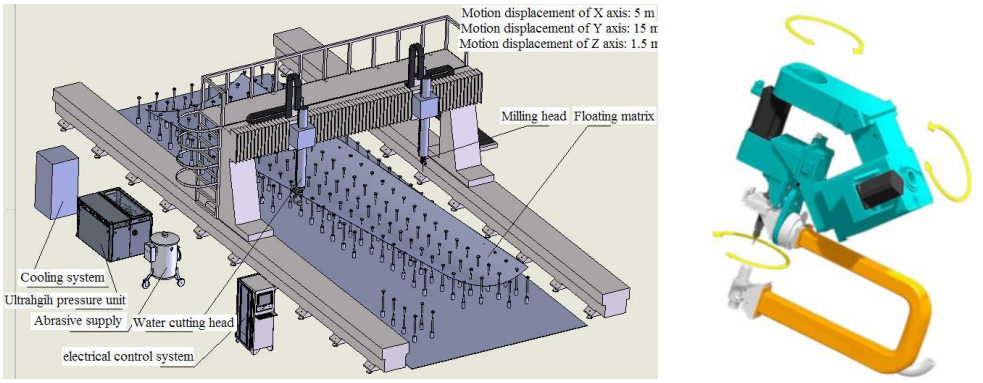
In order to meet domestic demand and respond to international competition level, author of this paper has undertook the 2015 year's National Advanced Technology Support Project of China research on ultrahigh pressure water cutting equipment and processing for composite and special high temperature resistant materials. The parameters comparison of equipments between this project prototype and other similar products at home and abroad are shown as follows (i.e., **Table 1**). We can see that the symbol of high-end ultrahigh pressure water cutting technology consist of large surface processing, extreme parameters, five-axis linkage, automation control of processing and measure, high precision, high speed, process parameters digital model and so on.

Table1. Technical Parameters Comparison of Domestic and Foreign Products

Flow Company of America	**PAR Company of America**	**Hefei General Machinery Research Institute of China**
Max. pressure: 420 MPa Working pressure: 385 MPa Flow: 3.79 L/min Power: 37 kW Position accuracy: ≤0.08 mm Repeatability of position accuracy: ≤0.06 mm Angle position accuracy: ≤14.4” Repeatability of Angle position accuracy: ≤7.2” Traverse velocity: 36 m/min Max. motion	Max. pressure: 420 MPa Working pressure: 385 MPa Flow: 3.79 L/min Power: 37 kW Position accuracy: ≤0.075 mm Repeatability of position accuracy: ≤0.025 mm Angle position accuracy: ≤14.4” Repeatability of Angle position accuracy: ≤7.2” Traverse velocity: 36 m/min Max. motion	Max. pressure: 500 MPa Working pressure: 450 MPa Flow: 6.0 L/min Power: 75 kW Position accuracy: ≤0.05 mm Repeatability of position accuracy: ≤0.03 mm Angle position accuracy: ≤10” Repeatability of Angle position accuracy: ≤5” Traverse velocity: 30 m/min Max. motion displacement of platform: 15×5×1.2 m Water cutting accuracy: Spot

displacement of platform: 14×4×0.35 m	displacement of platform: 15×4.5×1.2 m Water cutting accuracy: Spot which exceed ±0.75 mm is less than 0.3 %	which exceed ±0.75 mm is less than 0.3 %

It shows the assembly for large scale water cutting machine tools (i.e., **Figure 1**). Another picture shows the processing of aircraft wing (i.e., **Figure 2**). The test data are 120 mesh of quartz abrasive, 385 MPa of pressure, 435 mm/min of cutting speed, 400 g/min of abrasive consumption, 0.25 mm diameter of water jetting nozzle, 0.76 mm diameter of abrasive nozzle and 3 mm of cutting target distance.



a) Machine Tools Assembly b) Five-axis Linkage Water Cutting Head

Figure1. Large Scale Water Cutting Machine Tools

Figure2. Water Cutting Processing For Aircraft Wing

The assembly for large scale water cutting machine tools is made up of following parts [6].

1) Ultrahigh pressure cylinder booster system. It consists of double cylinder booster paralleled connected. Parameters of every cylinder booster are 450 MPa of pressure and 3L/min of flow. Cylinder body is double set and ultrahigh pressure-bearing parts are used 15-5HP. Plunger diameter of booster is 22mm, stroke of plunger is 100mm, and reciprocating times of plunger is

$70min^{-1}$.

2) Planer type water cutting platform. It uses gear and rack to drive, servo motor controller and software are used to control moving parts. Working size of platform is 15000×5000 mm, movement dimension of Z axis is 1200mm. The beam position of platform is measured with grating.

3) Floating matrix and flexible clamp system. It is made of 120 standard column brackets. They are used to support and position large curved surface component. Every column bracket has 3D rotary vacuum cup structure to flexible support and contact component surface. It can automatically adjust height and angle. The highest incensement of a column bracket is 600mm.

4) Five-axis linkage abrasive water cutting head system. It contains abrasive water cutting head, five-axis linkage assembly installed in electrical Z axis, C-shaped cup assembly, vacuum pump and abrasive collect pipe arranged on cross beam. During the operation, five-axis linkage assembly will drive abrasive water cutting head to make three-dimensional (3D) motion and lift along Z axis. The work piece will be kept in the middle of C-shaped cup assembly to cut. Abrasive waste after cutting will be kept in C-shaped cup which has silencer steel ball inside and synchronously suctioned by vacuum pump to liquid collector for solid-liquid separation.

5) 3D water cutting operation software. The core function of this software is to coordinated control five-axis linkage assembly and floating matrix system. That means it will identify the surface, regulating adhesion surface and control water cutting head operation along the curved edge of component. Because the software increased synchronization action for floating matrix system, the operation of software becomes a key technology.

6) On-line measuring system. It sets two vertical shafts on the beam. One shaft is Z axis for water cutting head, another shaft is for machine tool spare and on-line measurement probe. Though the measuring system, it can make implementation of automatic integration control for the whole processing, measurement and regulation.

3. ROUGH WATER CUTTING PROCESSING AND MICRO WATER CUTTING PROCESSING

It seems that water cutting can processing any mechanical parts like other machine tools when ultrahigh pressure water jetting technology successfully combine with five-axis linkage. However, the force of water jetting varies greatly under different water jetting target distances. Because the effect target distance of water jetting is very short, it limits the size of work piece. It makes water cutting edge precision difficult to have a clear performance. It needs to leave processing allowance like other machining. The processing allowance is difficult to be eliminated by water cutting process, because water cutting is like a flexible tool rather than a rigid tool.

Nevertheless, it is still a great rough machining to water cutting material with leaving processing allowance. Particularly it is important for the aviation industry to processing large

turbine impeller. In order to ensure the position accuracy, the traditional turbine impeller molding is to separate processing blades and turbine. Then it will weld or connect blades and turbine to become turbine impeller, thus there are problems of root strength and precision. Integrated machining has been a pursuit. Although there is five-axis machining center, the whole process of turbine impeller is still huge. It needs to cut layer by layer and the CNC programming is very complex. Water cutting for rough machining is a good solution to this problem. It can disposable cut the surface along the edge of work piece to processing allowance, to ensure sharp point and transition arc of any twisted surface and junction surface. Such a rough water cutting greatly improves efficiency for the whole processing of turbine impeller, and processing allowance can be secondary operation by machining center or finished by electrochemical processing. Position problem of secondary precision operation is solved by the consistency of these two processing operation software.

It shows rough water cutting example of large turbine impeller (i.e., **Figure 3**). There are two key technical problems. They are, using ultrahigh pressure and large flow pre-mixed abrasive jetting technology to improve water jetting effective target distance for large curved surface component; five-axis linkage makes water cutting head 60 degree layout to Z axis for processing with relatively large curvature.

Figure3. Rough Water Cutting Processing For Large Turbine Impeller

Micro water cutting processing is another development based on water jetting process. It is specifically for precision processing of sheet materials, composite materials and precious metals. These materials are emphasized no kerfs and quite precision processing, that is no great changes of dimensions before and after cutting, especially cutting for acute, narrow and complex pattern.

The workload of micro water cutting is not huge and there is no cutting speed requirement. However, if it wander to complete micro water cutting well, there are two following processing for different materials. One processing is fine abrasive water jetting, that is to use more than 150 mesh fine abrasive water jetting to reduce water nozzle diameter and flow which is based on high-end ultrahigh pressure water jetting. Another processing is 450MPa or even higher water jetting on the basis of ultrahigh pressure water jetting. Water jetting velocity is more than 3 times of supersonic velocity.

The accuracy targets of micro water cutting are ± 0.01 mm of abrasive water jetting

reproducibility accuracy, ±0.067mm/min of water jetting linear accuracy and 10,000mm/min of water cutting speed. The example shows a micro water cutting (i.e., **Figure 4**).

Figure4. Micro Water Cutting Processing

4. MULTIFUNCTIONAL CHARACTERISTICS OF ULTRAHIGH PRESSURE WATER CUTTING

Author of the paper has undertaken two sets of prototype from two directions. They are special large curved surface composite material water cutting equipment for air wing and ultrahigh pressure multifunctional water jetting CNC center for space high temperature resistant parts. The target of latter's technology is to apply water jetting technology to realize milling, drilling, polishing and other process. It is to make high temperature resistant parts of HRC70 machinable.

It shows the manufactured prototype (i.e., **Figure 5**), namely five-axis linkage ultrahigh pressure water cutting compound with two axis motion work piece platform. The latter platform can adjust the machined surface of work piece to adapt to water jetting direction. Relative movement between water jetting and work piece are controlled by software. With special water milling and water cutting head, multifunctional ultrahigh pressure water cutting CNC center is developed.

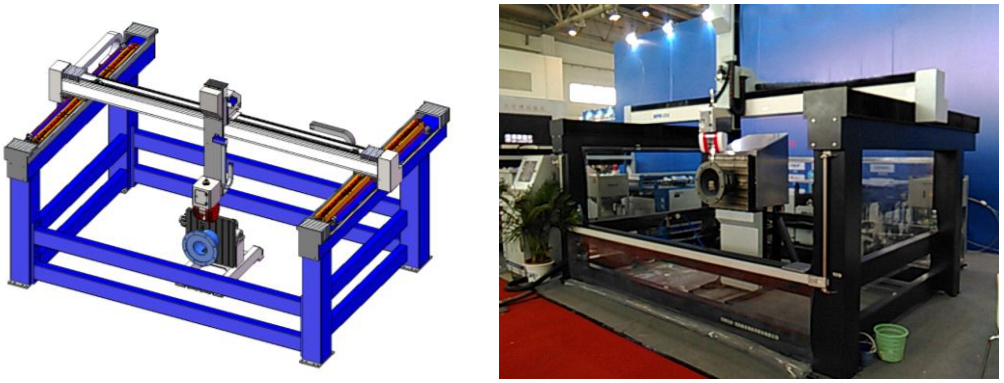


Figure5. Ultrahigh Pressure Multifunctional Water Jetting CNC Center

Application of multifunctional water jetting CNC center includes as followings.

Water turning process, that is to clamp work piece rotation and ultrahigh pressure water jetting traverse along axial direction of work piece (i.e., **Figure 6**). Limited to efficiency of water turning process, this process is only used for special materials such as composite material.

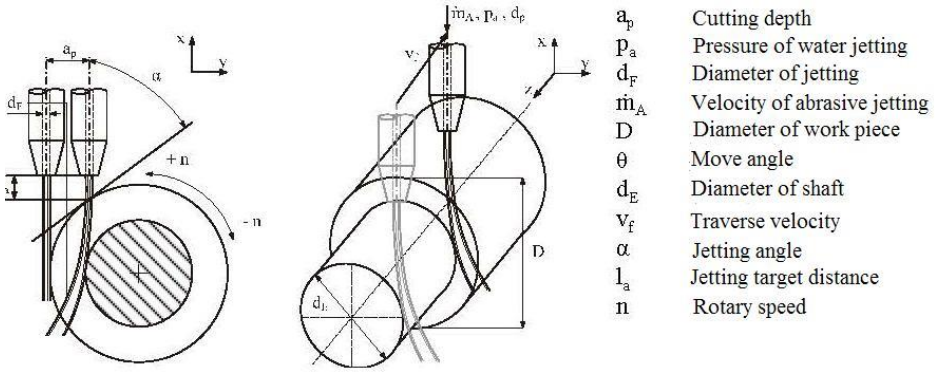


Figure6. Principle of Ultrahigh Pressure Water Turning

Water milling process, under the cooperation of both platforms, ultrahigh pressure water milling can be used to processing at any angle. It is not only suitable for special material, but also can compensate for mechanical milling process.

Like water milling process, water drilling process is also carried out by means of a template with a minimum hole of 0.3mm. Principle of water drilling process, especially for drilling profiled hole, is the same to principle of water cutting process.

Because water jetting is a non rigid contact process, it cannot be grinded. Water polishing process use fan-shaped nozzle or rotary water jetting can realize polishing for material. And its roughness is related to choice of abrasives.

5. ULTRAHIGH PRESSURE WATER MILLING PROCESS AND DEVELOPMENT

Milling process is the most commonly used process of multifunctional processing. Its form is simply to cut material under depth control, which does not cut through the material. It is difficult to implement and control because it need to receive uniformity depth and smooth surface. Obviously, water milling process is not operated one time, but many progressive forming.

The principle of water milling process is shown as following [7][8] (i.e., **Figure 7**). Obviously, with increasing traverse speed (u) of abrasive water jetting (AWJ) more than the speed (u_0) of AWJ cut through work piece, that is $u>u_0$, it is not to cut through material. And it will reduce cutting depth, even slightly depth. The bottom surface of work piece firstly becomes irregular surface, then rough surface and finally smooth surface. When AWJ traverse speed increased from 5 mm/s to 5000 mm/s or even higher, it can be inferred that bottom surface will be smoother, more uniform and straight. It can be said that larger traverse speed is a good solution for contradiction between control of water milling depth and surface precision index of work

piece.

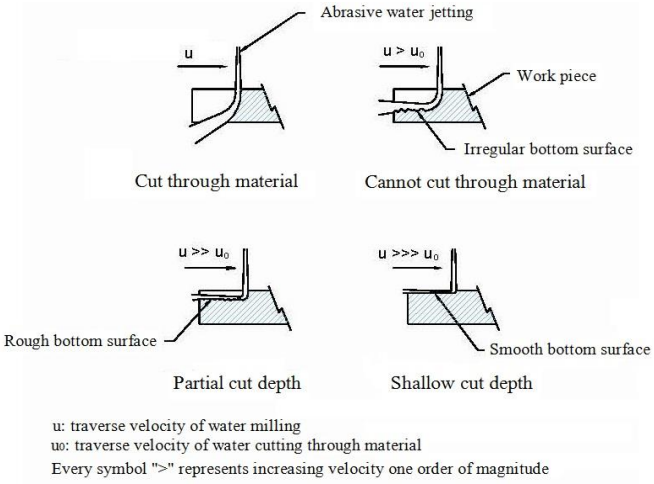


Figure7. Change From Water Cutting To Water Milling Under Traverse Velocity Of AWJ

The simplest model of water milling process is to keep milling template sticking on work piece, abrasive water jetting milling along the template (i.e., **Figure 8**). As for surface marks after abrasive water jetting, the jetting of next water milling process will be slightly regulation to eliminate surface marks. This process with template will milling groove, firstly milling the dividing line, then removes most of material in the middle. Abrasive water jetting is used to milling vertical angle. It is set 100 degree to milling surface and it is benefit for remove a large number of materials.

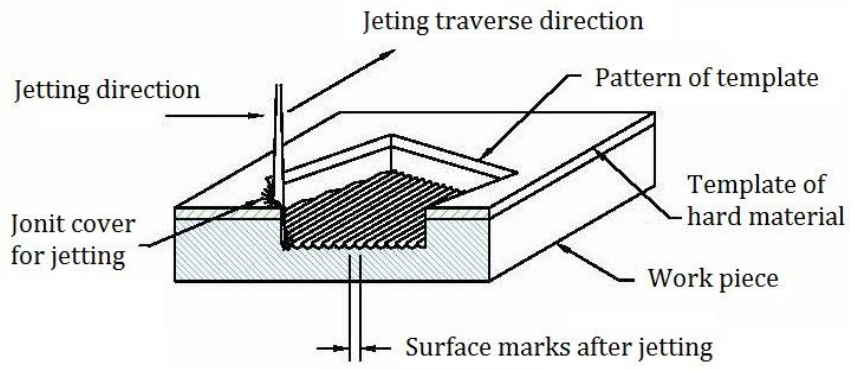


Figure8. Water Milling With Template

The following is a case record of water milling for composite material (i.e., **Table 2**), which can also be applied to water drilling and water polishing process.

Table2. Water Milling Experimental Data of Composite Material

Item	**Parameter**
Working pressure (MPa)	400
Abrasive	Garnet
Mesh	120
Jetting angle	90^0

Jetting target distance (mm)	1.0		
Abrasive nozzle (mm)	Φ0.89，L=101.6mm		
Water nozzle (mm)	Carbuncle Φ0.33		
Experimental pressure (MPa)	250	275	350
Abrasive consumption (g/s)	5.3	6.0	6.8
Jetting traverse velocity (mm/s)	10	15	19

The pictures show water milling of work piece with a template (i.e., **Figure 9**). It is milling a grid of geomagnetic lines on a 2.4m diameter reflecting telescope. The water milling depth is 2mm.

Figure9. Water Milling Processing Example

6. CONCLUSIONS

Ultrahigh pressure water jetting (500MPa, working pressure less than 450MPa) application can be very good for high precision and high difficult cutting process of composite materials. Moreover, it is to combination with five-axis linkage water jetting, floating matrix and flexible clamp system, workbench and so on. The water jetting process can be used multifunctional applications such as water milling, water turning, water drilling and water polishing of large curved components. Especially in the use of template matching with the experimental conditions, the experimental results show a good precision processing of large size composite water milling. The best water cutting condition of turbine impeller rough processing is ultrahigh pressure pre-mixed abrasive jetting, five-axis linkage makes water cutting head 60 degree layout to Z axis.

Acknowledgments

The work of the paper is supported by the National Advanced Technology Support Project of China (2015AA043401).

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