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Design and Experiment Research on Abrasive Water-jet Cutting Machine Based on Phased Intensifier

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Abstract: To solve the problem of water pressure fluctuation caused by the traditional double-acting intensifier, the paper has designed abrasive water-jet cutting machine based on phased intensifier as well as open numerical control system. The structure of cutting machine as well as the hardware structure and working principle of phased intensifier are introduced. The phased intensifier employs a constant pressure variable capacity pump to provide power, compressed air to push piston back, PLC to control working sequence of two pistons, making the structure of mechanism and control system to be simplified. Experimental research on several typical materials cut by water-jet cutting machine equipped with phased intensifier is conducted, which is valuable for design, manufacture and technological application of high pressure water equipment. It is practically proved that this system can work stably, with fluctuation rate of water pressure no more than 2.0%, as well as good cutting quality and high production efficiency.

Keywords: abrasive water-jet cutting; phased intensifier; numerical control; cutting experiment

1. INTRODUCTION

High-pressure abrasive water-jet (AWJ) cutting is a new process and technology that has developed a lot in recent years. In 1971, the sample of high pressure water-jet cutting machine appeared in the United States, and it had cut a variety of non-metallic soft materials. In 1983, abrasive water jet cutting technology came into use first time in the United States. It was used to cut all types of metal or non-metal, plastic or hard brittle materials. The principle of high-pressure water-jet cutting is to increase water pressure to an extra high pressure (400MPa) through a small hole (diameter of 0.15-0.4mm), then potential energy of water pressure is transformed into water-jet kinetic energy (the speed is up to 900m/s). The work piece can be cut by the high-speed intensive water-jet. Abrasive water-jet cutting is to mix abrasive particles in the water-jet, forming abrasive jet through abrasive mixing pipe (diameter of 0.9-1.5mm) to cut work piece. In the abrasive jet, water-jet is the intermediary used to accelerate the abrasive particles. Compared with water jet, owing to its high quality and hardness, abrasive jet has higher kinetic energy and cutting effectiveness.

The water-jet cutting material is wide, and it has high cutting precision, no thermal effect, and no pollution during the cutting process. At present, the high pressure water-jet cutting equipment has already been applied in the industry fields widely, such as aerospace, automobile, textiles, building industry and building material, mining, shipping, petrifaction, military industry as well as special metal working. It is the fourth generation cutting technology following flame, plasma and laser cutting technology (A.W. Momber and Kovacevic, 1997; M.Mazurkiewicz, 2000; Labus T., 1995; Zhao chun hong and Qin xian sheng, 2006).

To solve the problem of water pressure fluctuation that produced in water-jet cutting based on the traditional double-acting intensifier, the paper designs the open water-jet cutting numerical control system that is composed of the industrial personal computer and PMAC motion controller, and introduces the principle and the constitution of the water-jet cutting platform system. The third part of this article analyzes the working principle and disadvantages of traditional duplex reciprocating intensifier, designs the phased intensifier system, and introduces its working principle and the realization of the control system. The compressed air drives the piston back in this intensifier, thus the machinery and control system structure of the intensifier is simplified. Finally, the experimental study on water jet cutting technology is conducted, and the research result has guiding significance and practical value in exploitation and application of water jet cutting technology.

2. STRUCTURE AND WORKING PRINCIPLE OF ABRASIVE WATER-JET CUTTING MACHINE

The system components of abrasive water jet cutting machine are shown in Figure 1. Its composition and waterway process is shown below: water supply system—intensifying system—high pressure waterway system—abrasive material supply system—AWJ cutting head device (driven by the motion control system)—receiving device. The machine body is designed into platform structure; and the gear-rack is adopted to drive the cutting head, so that the accuracy and reliability of the cutting machine can be improved.

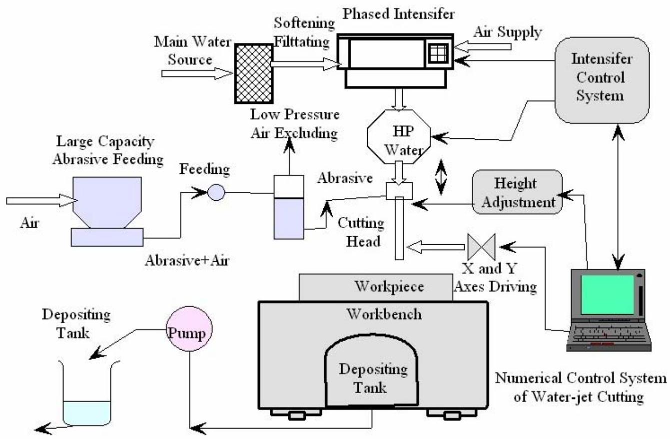


Fig. 1. The schematic diagram of water-jet cutting platform system

The pressure of water supply system is 0.4-0.9MPa, and it can soften the low pressure water, making the PH value between 6-8, and being filtrated below 0.5 μm . So that the abrasion and jam of sapphire nozzle can be avoided, the impact of corrosion of water quality to high-pressure waterway be reduced, the life of high-pressure reciprocating seal be enhanced. Intensifying system is the key of equipment, and its core is phase- intensifier. The pressure ratio of the intensifier is equal to the ratio of the piston's area of the big and small end. It is a constant, so the output hydraulic pressure of intensifier can be adjusted through changing the oil pressure of the input hydraulic system.

High-pressure waterway system connect intensifying system with cutting head device in order to transport water to and adapt to cutting head moving fast and freely in the movement control system. Ultrahigh-pressure stainless steel tube and rotary joint are adopted in high pressure waterways. The steel tube should have flexibility, and all joints should be reliable, compact, and flexible. Rotary joint should have a variety of rotary direction types and certain working life. Abrasive supply system includes hopper, abrasive, abrasive flow valves and duct. The shape and mesh screening of storage silo guarantee abrasive supplying swimmingly, avoiding jam. Flow valve controls the amount and the on-off of abrasive flux, and eliminates the water in duct. Receiving device is placed below the cutting head and work piece, which is used to collect remaining jet during cutting. It has functions of energy dissipation, noise reduction, splash preventing and so on. The bottom of the receiving device is covered with grit of 130-150mm, so that the remaining kinetic energy of water jet can be eliminated. Practice shows that the exposed water jet will create noise up to 120 dB (A), and the noise is controlled below 80-90dB (A) after receiving device is installed. Abrasive water jet cutting head includes water jet, mixing pipe and mixing chamber of abrasive. Numerical control system and control software can meet control requirements of various ultrahigh-pressure water cutting technology and cutting path. The non-contact height adjustment system makes the cutting head float with the work piece's surface. It can maintain a fixed hanging distance to ensure cutting quality, and can effectively avoid cutting gun being destroyed. Security monitoring system can finish water supply electronic detection, electronic oil surface level control and oil temperature control, and automatic cut off when ultra-high pressure and ultra-low pressure is detected,.

3. PHASED INTENSIFIER SYSTEM

The water pressure is increased from several mega Pascal to hundreds of mega Pascal by the intensifier in water-jet cutting. In order to obtain an approximately continue jet, traditional duplex reciprocating pump (DRP) is designed into double-acting pump, with two high pressure cylinders are joined with the back towards each other. When each travel of double-acting intensifier is finished, piston will reverse, which pressurizes the liquid in the reversed high pressure cylinder. At the same time the high pressure cylinder is filled with water again. From the mechanical characteristics of the design, we can know that the pressurized phases of two high pressure chambers are always reversed (180 degrees). Because the water can be compressed 12% under the pressure of 420MPa, the initial stage of the piston travel is used to compress the water. When hydraulic pressure of the water is larger than the hydraulic pressure of the water in the high pressure pipeline, the water outlet non-return valve is opened. Then, the water in chamber could be output. Therefore, the actions of draining water and absorbing water are discontinuous, and the pressure is fluctuant. To smooth pressure fluctuation, it is necessary to place an accumulator behind the intensifier, which is used to input water to high-pressure waterways in the first 1/8 stroke of the intensifier piston (Wei xin, 2001).

3.1 Phased intensifier and its control system

The phased intensifier employs two independent intensifier pistons, and two separated high pressure chambers, thus the pressure of two high pressure chambers is not always opposition. Under the control of this system, the time of absorbing water travel is shorter than the time of draining water travel. Before one chamber finishes the draining water travel, the other one has started the compressing travel. When one piston stops and going to reverse, the other one has compressed and drained the water in the other chamber. Therefore, there is no intermission in the complete circulation of absorbing water and draining water. Theoretically, the pressure fluctuation of draining water can be avoided. The phased intensifier system schematic diagram, which is shown in Fig. 2, mainly consists of the constant pressure control system of variable capacity pump, the hydraulic pneumatic system (driving the piston of intensifier to move back and forth) and the PLC control system.

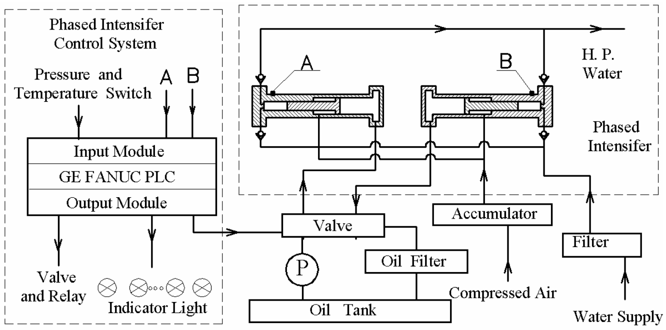


Fig.2 Phased intensifier system

When the system is working, the axial plunger pump presses the oil in tank into the low pressure chamber of intensifier through the reversing valve to push the piston. Through the channel of reversing valve which is controlled by the control system, hydraulic oil and pressurized air drives the piston of intensifier to move left and right. The two high pressure cylinders of intensifier alternatively do the actions of absorbing low pressure water and draining high pressure water under the control of the non-return valve. Thus the water pressure is increased to super high pressure. In phased intensifier, the piston movement of two cylinders is completely independent. The PLC control system generates coordinate sequence control signals to produce the uninterrupted water pressure correctly. Eddy current type approaches transducers A and B are used to determine two piston positions in the system. When transducer A transfers a detected signal into PLC, the PLC sends out the control signal to drive solenoid valve, which makes the hydraulic chamber of right intensifier and oil pump connected. The hydraulic oil drives pump piston to pressurize the water, and the high pressure water is transported to the cutting head under the control of non-return valve. At the same time, the left intensifier piston still move towards left and output high pressure water. The control program sends out the control signal after delay to drive solenoid valve, which makes the hydraulic chamber of the left intensifier connected to the tank. The compressed air drives the pump piston towards right to complete the action of absorbing low pressure water and draining hydraulic oil. Because the time used for absorbing water is shorter than that of the pressing water, the left pump piston stops moving at the end of the absorbing water travel. It will not start the next circulation until transducer B signal is detected.

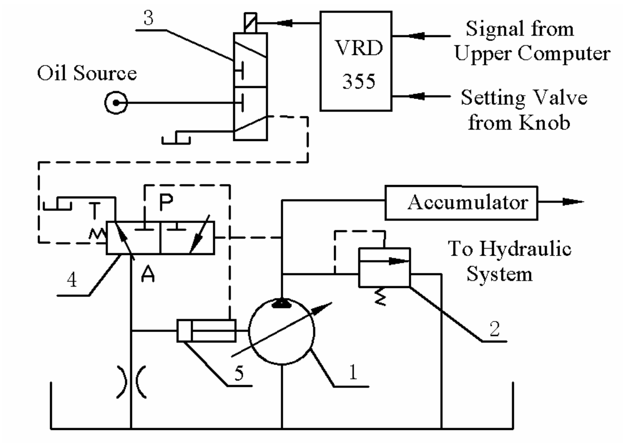
The core of this control system is GE FANUC 90-30 PLC. It completes the coordinate control of two intensifiers, and real-time monitors of hydraulic oil, pressure of high pressure water and compressed air through transducer. The system carries out corresponding processing and breakdown display when the system pressure is abnormal. Compressed air drives the piston back in the system, and the piston travel end is decided by the mechanical structure, which reduces the number of position transducers and simplifies the structure of intensifier mechanical and the control system. Owing to the adoption of the phase control method, the intensifier has no water hammer phenomenon. The noise is decreased, and the life of equipment is also lengthened. The entity of the intensifier is shown in Fig.3. The 316-type stainless steel is used for the high pressure cylinder, and titanium metal is used for its partial outer layer. This design lengthens the cylinder life, and the air cooling of intensifier is permitted, which reduces the cost of equipment manufacturing as well as the service. It is proved that the pressure of this system is stable, and its performance is better than traditional duplex reciprocating pump obviously.

3.2 Constant pressure control system of variable capacity axial plunger pump

Owing to high output power, reasonable working conditions of variable capacity axial plunger pump and high energy efficiency, it is selected as power supply of the system.

Fig.3. Picture of the intensifier

The constant pressure variable capacity axial plunger pump system is mainly composed of the pump, the variable capacity cylinder, the constant pressure valve, the high speed on-off valve and the control system. System principle diagram is shown in Fig.4. The high speed on-off valve 3 takes the role as the pilot operating valve. The output pressure is controlled by the PWM signal which is produced by the digital amplifier VRD 355 of Parker Corporation. This pressure signal acts directly on the left side of constant pressure valve 4 of constant pressure variable capacity pump, which adjusts output pressure of pump according to high speed on-off valve output pressure. Because pressure control loop of high speed on-off valve has the functions as the proportional control, and the pressure proportional control can be realized by electro-hydraulic control system. We take it as the interface part, which can control the output pressure of constant pressure variable capacity pump on the control panel. This design satisfies the requirement of different operating mode according to the stepless regulation of output pressure. This control system is an open-loop system, and VRD 355 can set the pressure value according to the turn knob of intensifier control panel. The analog signal of 0-10 volts which is output by the numerical control system can also be set to control pressure.



1 variable capacity axial plunger pump 2 overflow valve 3 high speed on-off valve 4 constant pressure valve 5 cylinder

Fig.4. Constant pressure control system of variable capacity axial plunger pump

System pressure acts on the right side of slide valve 4 when the hydraulic system is working, being balanceable with the sum of spring force and high-speed on-off valve's control pressure. When the pressure's balance is destroyed owing to the load's change, if the pressure's effect is larger than he setting force of left side, the slide valve will deviate equilibrium position to the left side, pressure oil come into the big end of variable cylinder, making the inclined plate mechanism of pump move, reducing the output flux of pump, thus the load pressure namely the system pressure is reduced, the pressure generates feedback to the right side of slide valve, until reaching balance again, namely the valve is closed. Conversely, if the pressure's effect is smaller than the setting force of left side of slide valve 4, the slide valve moving to the right side, releasing the pressure of the big end of hydraulic pressure cylinder, the inclined plate of the pump moving reversely by the effect of the small end's pressure, increasing the output flux of pump, so the system pressure is ascended, until the slide valve is balanced. The automatic pressure regulating process will make the system pressure keep constant without changing with the load pressure (namely setting value). When the system is working and the cutting head is open, the working pressure of the pump doesn't exceed the setting pressure, at this moment the pump works at the largest flux or any arbitrary flux below the largest flux. When the cutting head is closed, the pump stops output flux when the system pressure is larger than the setting pressure. Phased - high pressure water pressure fluctuations and the DRP-high pressure hydraulic pressure fluctuations are compared in Fig. 5.

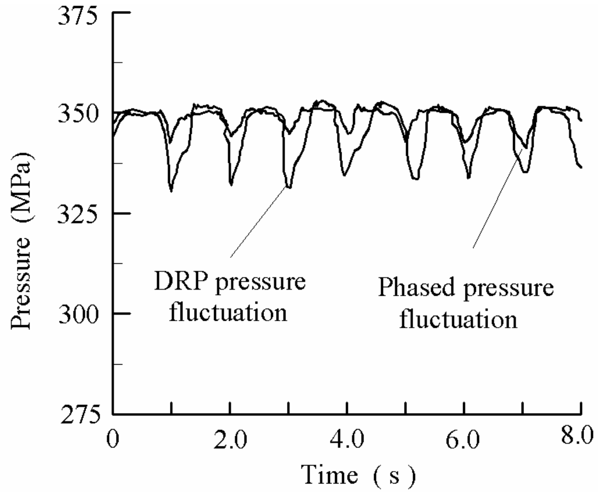


Fig.5. Comparison of pressure fluctuation of phased intensifier and DRP intensifier

3.3 Numerical control system

Numerical control system and control software is the control kernel of water-jet cutting system, and it communicates with the high-pressure pump control system to control the intensifier. The control software establishes the expert database to realize the computer aided cutting function. It completes the movement control of two-dimensional platform system, and realizes precise cutting of work piece. System button management and external movement control are realized through the common I/O port of numerical control system. The constant pressure control system of variable capacity plunger pump is controlled by the analogy quantity output port of numerical control system, which realizes stepless regulation of high pressure water and satisfies the cutting requirements of different thickness of work pieces. The numerical control system and the intensifier control system realize their communication through RS232 serial port connection. When breakdown or rapid stop appears in the intensifier and platform system, the whole system is stopped to guarantee the system security at the same time.

The open numerical control structure is adopted in water-jet cutting numerical control system. The reliable industry computer is employed as basic system hardware. And the Windows 2000 operating system is used as software platform which cooperates with the PMAC motion control card to complete movement control. The control software is developed by Visual C++ 6.0. The control system can receive the graphs generated by AutoCAD, and import and edit the Dxf format files. The water flow is closed automatically when the graph which is cut is changed. The water valve, overflow valve, and sand feeder valve can be started in turn manually or automatically, and the sequence and delay time can be set arbitrarily. The cutting direction can be set clockwise or counter clockwise, and the breakthrough point can be selected. The G code can be exported to other type equipment. During the cutting process, position and graph can be displayed real-time. Manual programming can be very convenient; and the track length can be calculated automatically. Furthermore, the total time and expense of processing can also be calculated. It is flexible and convenient to use the date and the time setting as well as password protection function. Besides, it can do the cutter compensation of "water cutter" to guarantee the cutting accuracy of work piece.

4. CUTTING PROCESS EXPERIMENTS

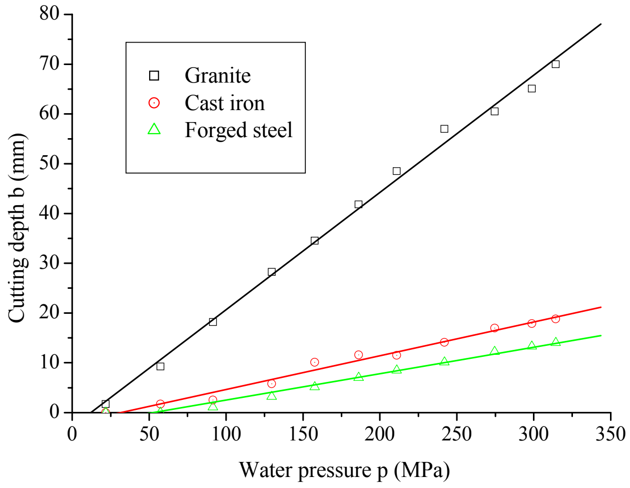
Abrasive Water-jet Cutting is a very complex process, and there are many parameters that can influence the performance of water-jet cutting (Brandt S, et al, 2000; Hashish M., 1984; Zeng J. and Kim T. J., 1993; Zeng J., et al, 1999)which includes kinetic parameters (water nozzle diameter, and hydraulic pressure), abrasive parameters (abrasive material, size, and quantity of flow), abrasive nozzle parameters (diameter, length, and material), cutting parameters (cutting speed, target distance, impact angle, and times of cutting), work piece parameters (hardness). But the process parameters that are easily controlled mainly include hydraulic pressure, abrasive parameters, cutting speed and target distance.

A lot of scholars have carried many researches on the cutting capability of ductile materials, brittle materials and composite materials by abrasive water-jet cutting. Through research (M. Hashish, 1984; L.Chen, et al ,1996; J. Wang, 1999) have found that regardless of ductile materials, brittle materials and composite materials, their abrasive water-jet cutting process exists in three areas: small angle cutting area, big angle cutting area, and jet upward migration area.(Mustafa, 2002; J. Wang, et al , 2002)studied influence of process parameter on the cutting quality of different materials through experiments. According to the requirements of industrial cutting, abrasive cutting machine equipped with phased intensifier is selected as the experiment platform, and cutting technological researches on granite, forged steel and cast iron are carried. Main technological parameters of cutting experiment system are: high-pressure water pressure $p \le 400MPa$, high pressure water flux $q \le 5L/\min$, cutting feed speed $v \le 9m/\min$, target distance $s \le 240mm$, and abrasive feed quantity $m = 0.1 - 0.8kg/\min$.

4.1 The relationship between cutting depth and water pressure

Fig.6 shows the relationship curves of cutting depth and water pressure of granite, forged steel and cast iron. In the figure, d_n is diameter of the water–jet nozzle; d_m is diameter of abrasive mixing pipe; m is Abrasive supply; n is Abrasive size; p is high-pressure water pressure; q is high-pressure water flux; s is target distance; v is cutting feed speed. As is shown in the figure, cutting depth is increasing linearly with increase of water pressure.

This is due to the increase of water pressure raises the velocity of the water-jet and the abrasive particle's kinetic energy is increased after being accelerated, thus enhancing material's abrasion and erosion effect.



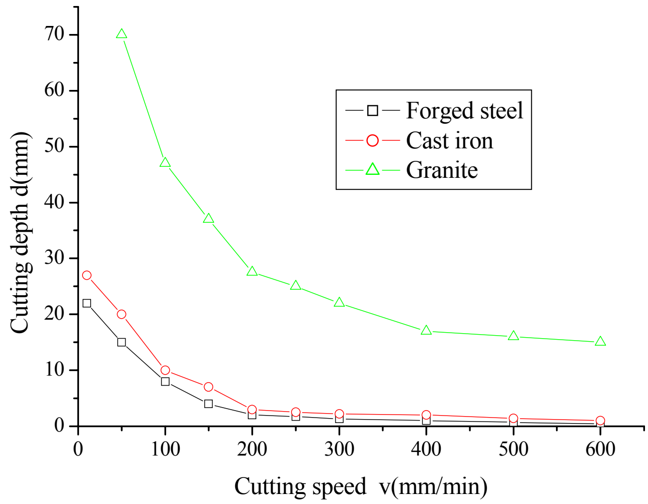
$d_n = 0.3mm \quad d_m = 1.2mm \quad n = 60$

$v = 100mm/\min \quad s = 3mm$

Fig.6. The relationship between cutting depth and water pressure

4.2 The relationship between cutting depth and target distance

Figure 7 shows the influence of target distance on the cutting depth of granite, forged steel and cast iron. It is seen that 2-5 mm is the best target distance existed corresponding to the largest cutting depth. When the target distance is more than 10mm, increased target distance can make the jet distribute on a larger surface area. The cut width on the material's surface is increased, and thus cutting depth is reduced obviously. The change of cutting depth to target distance of granite is more sensitive than forged steel and cast iron.



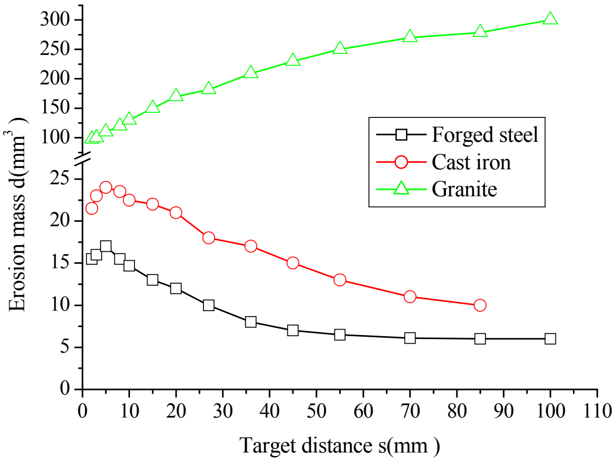
$p = 180MPa \quad d_n = 0.3mm \quad d_m = 1.2mm$

$n = 60 \quad s = 3mm \quad M = 0.27kg/\min$

Fig.7. The relationship between cutting depth and cutting speed

4.3 The relationship between erosion mass and target distance

Figure 8 shows the influence of target distance to erosion mass of granite. Erosion mass increases with target distance. When the target distance is bigger than 80 mm, the increasing trend of erosion mass becomes slow. The erosion mass reaches to $300mm^3/s$ when the target distance is 100 mm. Figure 8 shows that 2-5 mm is best target distance existed corresponding to the largest erosion mass. Target distance increases but erosion mass reduces, this is almost identical to the variation law of cutting depth to target distance.



$p = 180\ MPa \quad d_n = 0.3mm \quad d_m = 1.2mm \quad n = 60$
$Q = 2.6L/\min \quad M = 0.27kg/\min \quad v = 100mm/\min$

Fig.8. The relationship between erosion mass and target distance

5. CONCLUSION

The water-jet cutting platform system has been successfully applied in the industrial field. It is proved that the machine has small cutting error of workbench, high localization precision and production efficiency. The system is stable with quick response, and good man-machine interaction. The highest pressure of water-jet cutting system can reach 413 MPa, the output pressure fluctuation is smaller than 2.0%. The rate of successful perforation is above 98%, which guarantees the working efficiency and quality of water-jet cutting. The average non-breakdown time is more than 2000 hours. Based on phased water-jet cutting machine experiments on the relationship of cutting depth, water pressure and target distance, and the relationship between erosion quantity and target distance are conducted. The result has practical guiding significance for exploitation and application of water jet cutting technology.

REFERENCES

A.W. Momber and Kovacevic(1997). *Principles of abrasive water jet machining*, 264. Springer, New York.

M.Mazurkiewicz(2000). A manufacturing tool for a new century[J]. *Journal of Materials Processing Technology*, **106**, 112-118.

Labus T.(1995). *Fluid jet technology-fundamentals and applications*,128-176.Water-jet Technology Association.

Zhao chun hong, Qin xian sheng(2006). High-pressure water jet flow cutting technology and application. *Engine bed and hydraulic pressure,* **2**, 1-3.

Wei xin(2001). *The grinding compound water jet flow cutting machine based on controls the type pressure intensifier and the cutting model study*. Nanjing University of Science and Technology master's degree paper, China.

Brandt S., Maros Z., Monno M.(2000). *AWJ parameters selection, a technical and economical evaluation*, 353-366. U. K., BHRA.

Hashish M.(1984). A modelling study of metal cutting with abrasive water jets. *Journal of Manufacturing Science and Engineering,* **106(1)**, 88-100.

Zeng J., Kim T. J.(1993). *Parameter prediction and cost analysis in abrasive water jet cutting operations,* in Proceedings of the 7th American Water jet Conference, St. Louis, MO, 175-190. WJTA, USA.

Zeng J., Olsen J., Olsen C.(1999) . *The abrasive water jet as a precision metal cutting tool,* 65.

M. Hashish(1984). A modeling study of metal cutting with abrasive water-jets [J]. *Journal of Engineering Materials and Technology,* **106**, 88-100.

L. Chen, E. Siores, W. C. K. Wong(1996). Kerf characteristics in abrasive water jet cutting of ceramic materials [J]. *International Journal of Machine Tools and Manufacture,* **36(11)**, 1201-1206.

J. Wang(1999). Abrasive water jet machining of Polymer Matrix composites-cutting performance, Erosive Process and Predictive models [J].*International Journal of advanced manufacturing technology,* **15**, 757-768.

Mustafa(2002). Processes and apparatus development in industrial water jet applications [J]. *International Journal of Machine Tools and Manufacture,* **42**, 1297-1306.

J. Wang, D. M. Guo(2002). A Predictive Depth of Penetration Model for abrasive water jet cutting of Polymer matrix composites[J]. *Journal of Materials Processing Technology,* **121**, 390-394.