STUDY ON PARAMETER OPTIMIZATION FOR CUTTING SAFETY AND EFFICIENCY OF PREMIXED ABRASIVE WATER JET FOR HTPB PROPELLANT

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Some cutting tests were carried out on two kinds of HTPB (hydroxyl terminated polybutadiene propellant) including high and low burning rates with pre-mixed abrasive water jet. Influence of process parameters on cutting safety and efficiency under different cutting conditions was studied, and then theoretical basis was provided for parameter optimization. Single factor test method was selected to analyze their impact separately, including cutting speed (V), outlet pressure (P), abrasive concentration (T) and target distance (L) as the main influencing factors, and the maximum cutting depth was used as the measurement index of cutting efficiency. On this basis, orthogonal test was carried out to optimize the above parameters. The results show that the maximum cutting depth decreased with increasing cutting speed, and cutting area existed an optimum value in unit time; the maximum cutting depth increased linearly in certain range with increasing outlet pressure and tended to be gentle; both abrasive concentration and target distance had correspondence with the maximum cutting depth. The optimization results of orthogonal test show that cutting speed had more significant influence than target distance and other parameters. This study provided some theoretical support for the discard of HTPB propellants with premixed abrasive water jet as an engineered waste technology.

Keywords: safety engineering; premixed abrasive water jet; HTPB propellant; cutting

1. Introduction

Due to its special thermodynamic properties, removal of HTPB propellant from retired solid rocket engines is becoming a dangerous technical work, and study on safety and practicality in the process has become one of the hot spots in this field [1-3]. During more than 20 years, high-pressure water jet technology has rapidly developed a more efficient, economical, and environmentally friendly method for processing energetic materials, and its application in the military fields is becoming more and more extensive [4-7]. For example, the US and NATO leaded non-military disposal of conventional weapons, tactical missiles, rocket engines and energetic materials by the “take medicine” method for the failed pellets in engines that have expired missile engine life but can continue to serve after recasting. Especially, in the second round of nuclear weapons destruction in

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Ukraine in 1999, many solid engines on intercontinental missiles made use of high-pressure pure water jets to complete the disposal, and the maximum diameter reached Φ3m. On this basis, a guidance summary was proposed on the disposal of high-pressure abrasive water jets. In recent years, relevant domestic research institutes have tried to apply this technology to solid propellant separation, and got some valuable practical experience [8-10]. At the same time, the study on the relationship between the water jet parameters and the safety of the cutting process was exposed not systematic and in-depth, and the safety and efficiency of the high-pressure pure water jet on the solid propellant crushing effect is poor. Related studies have shown that the jet parameters are influential important factor in cutting efficiency of premixed abrasive jets [11]. As the most widely used rocket engine charge, this paper selected HTPB propellant with three components (AP/ Al/ max) as a research object, based on the erosion cutting theory of pre-mixed abrasive water jet under non-submerged conditions, using single The factor test method analyzes the effects of cutting speed (*V*), outlet pressure (*P*), abrasive concentration (*T*) and target distance (*L*) on cutting efficiency, and the optimization conclusion is obtained by orthogonal test. The results show that the cutting speed is the main factor that affects the cutting efficiency. The best parameters obtained from the test provide a certain theoretical basis and technical support for the application of the premixed abrasive water jet to the processing of rocket engine charging, which reduces the risk and improves the efficiency, The purpose of cost savings.

2. Test part

2.1 Test conditions

2.1.1 Cutting equipment

Premixed abrasive water jet cutting device produced by Baoding Ruixun Company in China was selected as test equipment, whose composition was shown in Fig. 1, including pressure generating device, abrasive device and control device, etc. The garnet with a size of 80 mesh was used as abrasive, and its Mohs hardness was 6.5 to 7.5, and its density was 3.6 to 4.2 $g \cdot cm^{-3}$. The operating mechanism of test equipment was introduced as follows: the pure water added beforehand and the abrasive in abrasive storage tank were thoroughly mixed in the water tank, and then the mixture of them was supplied to the pressurization system. The booster system drives the power matcher through a high-pressure piston pump to provide pressure to total system. From the pressure generating device, the abrasive slurry with a certain concentration can be prepared and delivered to the nozzle through a high-pressure hose, then form a premixed abrasive water jet. During the cutting operation, the material to be cut was fixed under the nozzle, and the servo mechanism was activated to move the material relative to the cutting device to complete the entire cutting operation.

Fig. 1. Test equipment

2.1.2 Research object

Two kinds of HTPB propellants with high burning rate and low burning rate were both selected as research object, and they were prepared into rectangular specimen with dimension of 100mm×100mm×200mm. The mechanical properties of HTPB propellants were shown in Table 1 [12].

Table 1

Mechanical property of HTPB propellant including high and low burning rate (20°C)

Technical indicator	HTPB propellant with high burning rate	HTPB propellant with low burning rate
compressive strength / kg·cm^{-2}	111.1 (10.88 MPa)	250 (24.48 MPa)
strength of extension / kg·cm^{-2}	41.0	63.0
ductility / %	6.0	7.4
failure elongation / %	6.3	8.1
shock strength / kg·cm^{-2}	5.31	8.32

2.1.3 Auxiliary temperature measuring device

The thermocouple named pt1000 was selected as temperature sensor, and its accuracy was 0.01°C. During the process of making propellant specimen, six temperature sensors were embedded into propellant along the cutting path of water jet evenly and connected to a six-channel recorder through wires. After curing, these thermocouples can provide the internal data of temperature rise in the propellant.

2.2 Test processes

There are 18 hydraulic and jet parameters for cutting technology of premixed abrasive water jet [13-15]. Limited by test conditions and equipment, only four parameters including cutting speed, outlet pressure, abrasive concentration and target distance were selected in the test, because they all have a great influence on cutting efficiency and safety, and they are all easy to be adjusted. Then the single factor test and orthogonal test for cutting safety and efficiency were carried out on the basis of four parameters. The parameter can be controlled by following steps: outlet pressure can be adjusted directly at instrument panel, and its range was 0-50 MPa; abrasive concentration can be controlled by sand valve, and its range was 10 to 70%; cutting speed and target distance can be adjusted precisely and continuously by the servo. Cutting test was designed to obtain the maximum cutting depth under the premise of that propellant specimen would not be cut off, as shown in Fig. 2. Data of the maximum cutting depth should be collected along the cutting direction and measured 3 times every 5mm with a Vernier caliper, and the average value should be taken as the final test data.

Fig. 2. Measurement of the maximum cutting depth

2.2.1 Cutting efficiency test

Single factor tests used HTPB propellants with high and low burning rate as test object. Because cutting efficiency was a time-dependent variable [16], the maximum cutting depth should generally be measured to compare the influence of parameters on cutting efficiency. However, cutting speed was also a time-dependent variable so that the cutting area per unit time that was the product of cutting speed and cutting depth was suitable for comparing its influence. HTPB propellant with high burning rate was selected as the test object, and the maximum cutting depth was selected as the target for the orthogonal test. Each parameter was also based on the safety test, but the range of target distance was appropriately expanded, and the orthogonal test table with 4 factors and 3 levels was finally established as shown in Table 2. The conclusions of selection and optimization of parameters should be combined with the results of both the single factor test and the orthogonal test.

Table 2

Parameter selection range for orthogonal test

parameters	outlet pressure /Mpa	cutting speed /mm·s^{-1}	target distance /mm	abrasive concentration /%	nozzle diameter /mm	gage length /mm	cutting angle /	grid size /mesh
HTPB propellant with high burning rate	30	2	1	30	0.8	50	90	80
	40	3	3	40				
	50	4	5	50				

2.2.2 Cutting safety test

Cutting efficiency test must be based on a stable safety test (internal temperature rises test and success or failure test). According to "hot spot theory" approximately, the internal temperature range in the propellant should not exceed 400°C [17], otherwise it was prone to occur some uncontrolled accidents such as burning or explosion. Through the preliminary test, some parameters were selected limit value, such as outlet pressure was 50MPa, cutting speed was 1.0mm·s^{-1}, abrasive concentration was 50%, and target distance was 3mm.

In addition, in order to ensure the reliability of test data, a success-failure safety test was conducted. The total of test piece was 474, which was punctured using an abrasive water jet and be recorded the process changes.

3. Analysis of test results

3.1 Effect analyses of cutting safety tests

3.1.1 Effect analyses of internal temperature rises test

Temperature rise inside two kinds of propellants were not obviously changed and the maximum temperature never exceeded 35°C before the specimen was cut off as shown in Fig. 3.

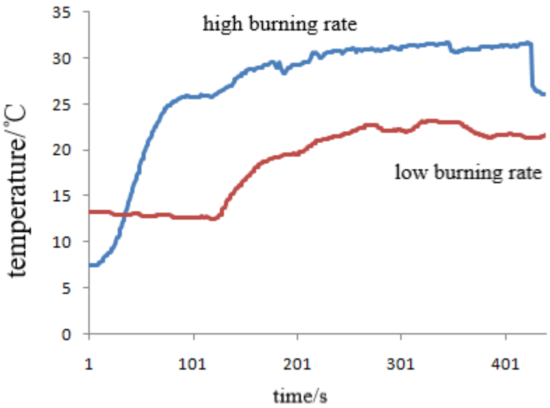


Fig. 3. Temperature rise during cutting

3.1.2 Effect analyses of success-failure test

Under certain process parameters, a total of 474 test pieces were perforated, none of which caused combustion or explosion. According to the unilateral lower confidence limit estimation method of binomial distribution in reliability theory, the failure probability without actual failure, that is the confidence level corresponding to the lower limit of reliability is the following formula:

$$c=1-R_n \tag{1}$$

The lower limit of reliability is following formula:

$$R=(1-c)^{1/n} \tag{2}$$

In the formula: n is the number of successful tests without combustion or explosion, and it is 474; when c is 0.9, then R is 0.9952.

According to above calculation result, the reliability of abrasive water jet cutting HTPB propellant without combustion or explosion is not less than 99.52% at a 90% confidence level.

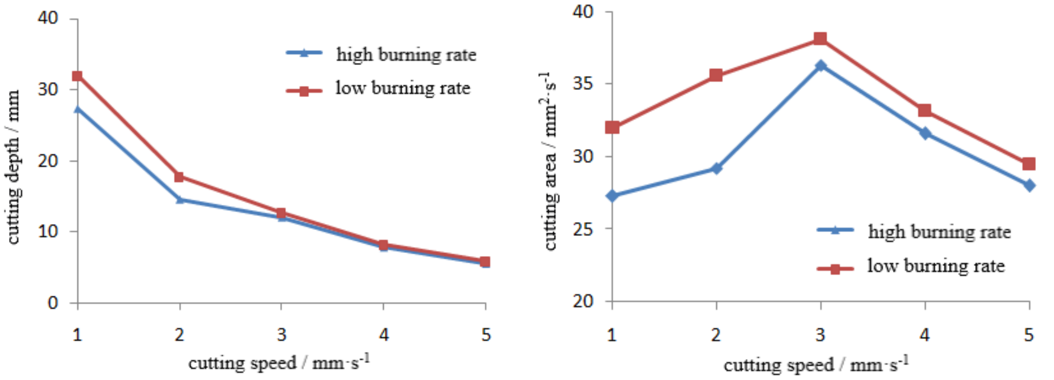
3.1.3 Effect analyses of success-failure safety test

Through internal temperature rises test and success-failure test, it can be judged that the cutting process is safe for the low-sensitivity three-component HTPB propellant. Because of the binder, the mechanical effect of the abrasive particles on the energetic substance of the propellant is limited, and the converted heat is quickly taken away by the large flow of water. Even in the cutting process, the weak sparks generated by the friction between the abrasive and the metal appear at any time in the cutting seam, but it soon surrounded by the cold high-speed water beam, and the water beam acts as a lubricant to reduce the friction between the abrasive and the propellant, thus the generation and growth of hot spots are suppressed, and the impact sensitivity of the propellant is reduced. In short, the low outlet pressure of the abrasive jet in a short time and the cooling and anti-friction effect are the decisive factors for suppressing the impact initiation of the HTPB propellant.

3.2 Effect analyses of single factor

3.2.1 Effect of cutting speed on cutting efficiency

Process parameters in such single factor test were set as following steps: outlet pressure was 30 MPa, abrasive concentration was 30% and target distance was 3 mm. As shown in Fig. 4a, the maximum cutting depth was inversely proportional to cutting speed, and tended to be gentle with the increase of cutting speed; it was foreseen that when cutting speed reached a certain value, the maximum cutting depth at this point was extremely low so that water jet may not useful in practical. Within a certain cutting speed range, cutting area first increased and then decreased, as shown in Fig. 4b. When cutting speed reached a certain value, the cutting area reached a maximum, when cutting efficiency also reached a maximum at this point. Therefore, the optimum cutting speed was so important that it should be devised through a lot of trial and error.



(a) Cutting depth (b) Cutting area

Fig. 4. Effect of cutting speed on cutting performance

The reasons were analyzed as following: First, as cutting speed increased, the water jet's energy per unit time was dispersed to a longer distance, which weakened the impact force on propellant per unit distance. At this time, the abrasive concentration does not change, that means the total number of abrasive particles contained in the water jet per unit time was constant, which will result in a corresponding reduction in the number of blows by the abrasive particles on the propellant. Due to the reduced energy utilization rate of this part of abrasive particles, the initial acceleration ability was weakened, and fatigue damage to the propellant cannot be produced, which was an important cause of the reduction of the maximum cutting depth. Second, as the cutting progresses, part of water jet energy was inevitably used to increase the width of slit, resulting in the cutting efficiency at this time was much lower than the efficiency under ideal conditions. As the cutting speed increased, both the slit width and the maximum cutting depth decreased, but the cutting efficiency existed a maximum somewhere in the effective range due to the increase in cutting efficiency. Once the corresponding cutting speed exceeds a certain value, the frequency and strength of abrasive particles in the edge region of a water jet can't finish the fatigue damage of propellant, and the number of hits for unit area was reduced. As a result, the overall energy utilization of water jet was reduced Eventually, the reduction in cutting efficiency results from a decrease in the maximum cutting area because of the maximum cutting depth reduction being greater than the effect of the cutting speed increase.

3.2.2 Impact of outlet pressure

The process parameters in this test were set as follows: cutting speed was 2.0 mm·s^{-1}, abrasive concentration was 30%, and target distance was 3 mm. As shown in Fig. 5, the maximum of cutting depth was approximately linearly increasing with the outlet pressure. According to the traditional theory, threshold outlet pressure of HTPB propellant was 11MPa under the pure water jet, when the cutting ability of premixed abrasive water jet was about 2.8 times that of pure water jet [18]. The threshold pressure under abrasive jet can be roughly calculated about 4 MPa. That is to say, the abrasive can only collide elastically with the propellant and cannot perform effectively cutting below this pressure. It was conceivable that the maximum cutting depth will continue to increase and its trend will continue to slow down after the outlet pressure exceeds 50 MPa. It showed that simply reducing the outlet pressure of pre-mixed premixed abrasive water jet had no practical engineering value for cutting propellant, because it was a soft viscoelastic body.

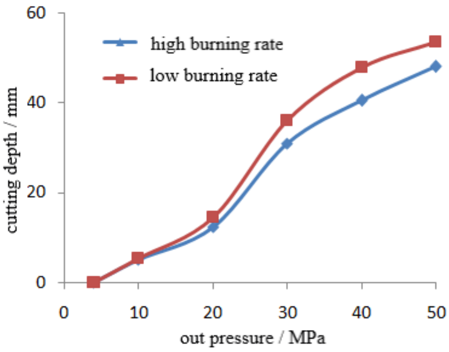


Fig. 5. Effect of outlet pressure on maximum cutting depth

Outlet pressure was a decisive factor in reflecting the energy of the premixed abrasive water jet. As the pressure of the outlet increased, the acceleration of water jet on the abrasive was obvious, which was reflected by the increase of the energy of water jet resulting in the impact of abrasive on propellant more obvious microscopically. Therefore, the cutting ability of a water jet was enhanced. However, the curve of the relationship between the maximum cutting depth and the outlet pressure becomes smoother subsequently. The reasons are analyzed that: First, the acceleration of abrasive was enhanced so that the effective target distance of water jet was increased, and the abrasive particles often fails to reach the optimal target after contact with the propellant. The energy of abrasive particles was not fully released, resulting in low energy utilization. Second, the collision among abrasive particles was intensified. The fracture of abrasive particles before contact with the propellant was severe, resulting in a smaller particle size. The loss was increased and the energy utilization rate was reduced. Thirdly, water jet will produce a "water cushion effect" after entering the slit, which will produce a strong reflection phenomenon and weaken the cutting action of the subsequent jet. It was also the main factor reason for the slow increase of the maximum cutting depth; and the greater the outlet pressure, the stronger the reflection. In the actual cutting process, it was not advisable to increase the cutting ability by increasing the outlet pressure. Because the advantage of pro-mixed premixed abrasive water jet was in the same cutting capacity under the lower the outlet pressure to ensure safe, and the outlet pressure was limited by the equipment itself (generally not exceeding 50 MPa). Therefore, the choice of outlet pressure should be based on the mechanical properties and physical and chemical properties of the material to be cut, and mountain the temperate principle.

3.2.3 Influence of abrasive concentration

The process parameters in this test were set as follows: cutting speed was 2.0 mm·s^{-1}, target distance was 3 mm, and outlet pressure was 30 MPa. As shown in Fig. 6, the relationship curve between the maximum cutting depth and the abrasive concentration increased firstly, and then decreased. Abrasive concentration represented the mass fraction of the abrasive in water jet, which was an important parameter determining cutting performance of premixed abrasive water jet and the only parameter that distinguishes the performance of pure water jet. As abrasive concentration increased, the maximum cutting depth increased significantly. A huge difference in cutting performance was shown between premixed pre-mixed abrasive water jet and pure water jet under the same working conditions. When abrasive concentration increased by 0 to 50%, the maximum cutting depth increased from 4.1 mm to 55.3 mm for HTPB propellant with high burning rate, and the amplify was 13.4 times; for HTPB propellant with low burning rate, the maximum cutting depth increased from 3.4mm to 45.7mm, and the amplify was 13.9 times. When the abrasive concentration reaches a certain value, the maximum cutting depth appeared a maximum value, and then gradually decreased.

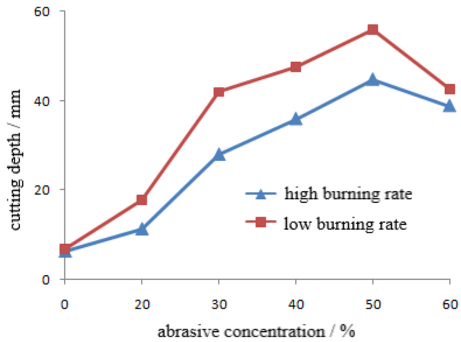


Fig. 6. Effect of abrasive concentration on maximum cutting depth

High pressure water jet will greatly increase its energy utilization after the addition of abrasive, which was reflected as a significant increase in the maximum cutting depth. The reasons are as follows: First, according to the law of conservation of energy, premixed pre-mixed abrasive water jet had much larger force on the propellant than pure water, because the abrasive that obtained the energy has a larger density and an irregular shape; Second, as the concentration of the abrasive increased, the number of blows by abrasive particles to HTPB propellant per unit time increased; third, increased number of abrasive particles in the edge area of the jet beam increased the width of the slit, resulting in more abrasive particles to enter the slit to enhance fatigue of the propellant. Therefore, a continuous cutting action was acted to produce. However, the energy consumption of abrasive particles in the acceleration process can not be ignored. The related literature showed that the abrasive particles collide with each other when passing through the high-pressure tube so as to cause severe fracture, and the damage rate was as high as 80% [19]. If the abrasive concentration increased, that means the number of abrasive particles continues to increase, the collision among the abrasive, between abrasive and high-pressure delivery tube, and between abrasive and water will increase too, which gradually increases the internal friction of water jet energy. Therefore, when the abrasive concentration was increased to a certain value, the maximum cutting depth was reduced. At the same time, under the premise of constant jet energy, the increase of abrasive concentration will directly reduce the kinetic energy of the individual abrasive particles, resulting in weakening of the striking effect, which was also an important reason for the maximum cutting depth reduction. Therefore, without increasing outlet pressure, cutting efficiency can be greatly improved by increasing abrasive concentration within a specific range, but the optimum parameters should be found through trial and error, otherwise the equipment life, especially its nozzle, will be reduced, and the use cost will be increased.

3.2.4 Influence of target distance

The process parameters in this test were set as follows: cutting speed was 2.0 $mm \cdot s^{-1}$, outlet pressure was 30 MPa, and abrasive concentration was 30%. As shown in Fig. 7, as the target distance increases, the maximum cutting depth increases first, and then decreases continuously. There was an optimal parameter, and the optimal target distance in such conditions was 3 mm.

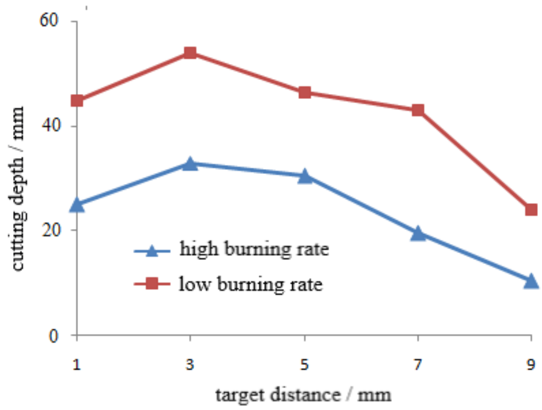


Fig. 7. Effect of target distance on maximum cutting depth

In general, after they removed from the nozzle [20], the acceleration of abrasive particles will continue until they had the maximum speed and cutting capacity. Premixed abrasive water jet will have the optimum target distance at a certain point. Immediately after the end of the acceleration process, premixed abrasive water jet entered the deceleration process for various factors. In this process, the energy loss increased, the cutting ability gradually decreased, and the maximum cutting depth began to decrease. The optimal target distance was related to the acceleration process of abrasive, which was determined by the initial energy source of water jet. That is to say, the optimal target distance of water jet was ultimately determined by outlet pressure. It can be seen from the experiment that the relationship between target distance and the maximum cutting depth under different outlet pressures was shown in Fig. 8. Since this test takes a long time and has nothing to do with cutting speed and abrasive concentration, HTPB propellant with high burning rate was only selected as the test object and cutting speed in the test condition was 4.0mm·s^{-1}, abrasive concentration was 10% in order to save time and cost.

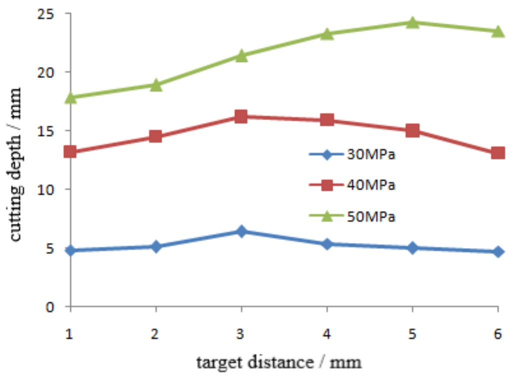


Fig. 8. Relationship between target distance and outlet pressure

It can be seen from Fig. 8 that an increase in outlet pressure causes a tendency for the optimum target distance to gradually increase. At lower outlet pressures, the maximum speed that abrasive particles can reach was relatively small, so the required acceleration distance was shorter. As the outlet pressure increased, the acceleration on abrasive particles increased, and both maximum speed and the required acceleration distance increased accordingly. In practical applications, the optimal target distance for water jet means the maximum cutting capacity. At the same time, attention should be paid to the correspondence between outlet pressure and the optimal target distance, and how to match them correctly to obtain the highest energy utilization rate.

3.3 Optimization of process conditions

It can be seen from the results in Table 3 that the extreme difference of four factors was extremely large, indicating that cutting speed was the main factor affecting cutting efficiency, and the other three secondary factors are target distance, outlet pressure and abrasive concentration. Therefore, the optimized test can be optimized as $V_1L_2P_3T_3$, and the condition was that target distance was 3mm, outlet pressure was 50MPa, cutting speed was 2mm·s^{-1}, and abrasive concentration was 50%, when the maximum cutting depth was 58.2mm obtained in the verification test.

Table 3

Analyses of orthogonal test results

Test number	Outlet pressure (P)/MPa	Cutting speed (V)/mm·s^{-1}	Target distance (L)/mm	Abrasive concentration (T)/%	Maximum cutting depth (H)/mm
1	30	2	1	30	48.3
2	30	3	3	40	38.1
3	30	4	5	50	23.3
4	40	2	3	50	49.6
5	40	3	5	30	34.6
6	40	4	1	40	24.8
7	50	2	5	40	47.2
8	50	3	1	50	39.8
9	50	4	3	30	26.5
M_1	109.7	145.1	112.9	109.4	-
M_2	109	112.5	114.2	110.1	
M_3	113.5	74.6	105.1	112.7	
R_i	4.5	70.5	9.1	3.3	

According to the above test results, the cutting efficiency of pre-mixed premixed abrasive water jet to HTPB propellant was affected by cutting speed, target distance, outlet pressure and abrasive concentration. Among them, cutting speed has the most important influence and existed an optimum value. In practical applications, appropriately reducing cutting speed was beneficial to exert the water wedge effect and accelerate the impact and peeling of the propellant. If cutting speed was too low, it may result in excessive slitting which was the reason for low energy utilization and energy waste. The increase of outlet pressure will cause velocity to become larger, thereby increasing the kinetic energy effect. It will increase the damage effect on contact surface in turn, which was reflected by the better cutting performance. However, due to the low mechanical strength of HTPB propellant, higher outlet pressure has no significant effect on efficiency, and blindly increasing outlet pressure will also generate energy waste and unknown risks. In short, it was not worth the candle. Therefore, the choice of outlet pressure should be based on cutting conditions in the reasonable and safe range, and the pursuit of the maximum value is meaningless. The factor of target distance has a relatively small effect on cutting performance. Because water jet has obvious rigidity characteristics in the initial stage, although there was a theoretical optimal target distance value, target distance will gradually increase with time, resulting in lower cutting performance. Therefore, the pursuit of the optimal target distance was also meaningless. Therefore, target distance should be mainly controlled in the initial section of a water jet, so that its influence can be ignored.

The flow rate of water jet was proportional to nozzle diameter of the cutting equipment. Under the condition that outlet pressure was fixed, abrasive concentration was the main factor determining cutting performance. Properly increasing the nozzle diameter was one of the effective ways to improve cutting performance. However, if abrasive concentration was at a high level, the consequences will be serious, including the severe internal energy loss, the reduced nozzle life and the greatly increased probability of “hot spots” in the impact process. Therefore, abrasive concentration should be selected as same as outlet pressure, which followed the appropriate principle and determined the optimal value after repeated experiments according to the actual situation.

4. Conclusion

Based on the cutting safety, the paper used pre-mixed premixed abrasive water jet to carry out the cutting test on HTPB propellant, and the following conclusions were drawn on the safety and optimization of water parameters:

Both the dense structure of HTPB propellant and the characteristics with low-pressure and high-energy of premixed abrasive water jet are important reasons to ensure the security of cutting process. Cutting efficiency test should be carried out with the above parameters as the upper limit for subsequent testing in principle.

In the single factor test, the maximum cutting depth decreases with the increase of cutting speed, and the cutting area per unit time increased first and then decreased. That mean there was the optimal cutting speed for cutting efficiency; when outlet pressure increased, the maximum cutting depth increased linearly within a certain range, and the increasing speed tended to be gentle. It indicated that the influence of outlet pressure on the cutting efficiency was gradually weakened; abrasive concentration can significantly improve the cutting ability of water jet, and there was the optimal value for the parameter; through increasing outlet pressure, the optimal target distance can be prolonged, and at a certain outlet pressure, the maximum cutting depth increased first and then decreased with the increase of target distance.

In the orthogonal test, the main factor affecting cutting efficiency (the maximum cutting depth) was cutting speed. The secondary factors were target distance, outlet pressure and abrasive concentration in order. The optimized test condition was $V_1L_2P_3T_3$. When outlet pressure was 50 MPa, target distance was 3 mm, cutting speed was 2 $mm\cdot s^{-1}$, and abrasive concentration was 50%, the maximum cutting depth was 58.2 mm in the condition

Premixed abrasive water jet was an effective cutting method for HTPB propellant, and it has great security guarantee and application prospect. In the engineering applications, operators should pay attention to properly reduce cutting speed to ensure the cutting performance. According to the actual situation, target distance should also be adjusted to ensure it in the initial segment in order to improve energy efficiency. The choice of outlet pressure and abrasive concentration should be based on the cutting requirements, and should not seek the maximum. If necessary, two above parameters should be appropriately lowered to ensure safety.

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