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Research Article

Experiment on Conical Pick Cutting Rock Material Assisted with Front and Rear Water Jet

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Conical picks are one kind of cutting tools widely used in engineering machinery. In the process of rock breaking, the conical pick bears great cutting force and wear. To solve the problem, a new method, conical pick assisted with high pressure water jet, could break rock effectively, and four different configuration modes of water jet were presented. In this paper, based on the analysis of the different water jet configuration's advantages and disadvantages, experiments on front water jet, new typed rear water jet, and the combination of those two water jet configuration modes were conducted to study the assisting cutting performance and obtain the quantitative results.

1. Introduction

Conical picks, one kind of cutting tools, are widely used in engineering machinery. Their low cutting efficiency results from impacting with stiff rock directly in the cutting and drilling progress. In most cases, the compressive strength of rock is over 40 MPa, which increases the resistant force on pick and results in failure (Figure 1) and low cutting efficiency of pick. Thus, it is significant to find a method to reduce the failure of picks and enhance the efficiency of rock breaking. How to reduce the resistance of rock to the pick must be taken into consideration. Many studies have been conducted on researching the cutting force and even the forces in three orthogonal directions.

Dominant rock properties affecting the performance of picks load were studied, which emphasized that uniaxial compressive strength among the rock properties investigated is best correlated with the measured cutter performance values [1]. Cutting tests were carried out on an established cutting test bed to analyze the relationship between cutting force and coal compressive strength, the carbide tip diameter, and the cutting depth. The results show that the cutting force is linearly related to the compressive strength and exponentially related to both the carbide tip diameter and the cutting depth [2]. Interference mathematical models of straight and revolving cutting were established according to coal cutting theory and carried out coal cutting experiments with different cutting angles, head face radii of pick body, and cutting depths to verify the mathematical model [3]. The cutting forces were researched under varying cutting geometries by means of a semiempirical approach and developed prediction equations of the peak cutting force and mean cutting force shown to be statistically significant by the regression analysis through analyzing the full-scale rock cutting test data [4]. Tool forces were numerically predicted from cutting tests in PFC 3D. Moreover, the peak cutting forces were calculated by utilizing the theoretical equations and the results of experimental studies were given as well. It was pointed out that there is a strong correlation between the modeling, experimental, and theoretical studies [5]. Numerical model of rock cutting processes with road header picks was presented, which is typical for underground excavation and tested the cutting (tangential), normal, and side components forces. Moreover, the results of the 2D and 3D analyses have been compared with one another, and numerical results have been compared with the available experimental data [6]. Permeable quartzose sandstone was subjected to full-scale cutting tests under a chisel-type drag pick in both dry and

(a) Picks used on road header

(b) Picks used on shearer

Figure 1: Picks out of work.

fully saturated conditions. The results indicate that saturation increases cutting forces by 9.9% and normal forces by 9.4% and increases the specific energy of cutting by 28% [7]. The tool forces were recorded, in three orthogonal directions, during the numerical simulations using a discrete element method, which indicated that that the influence of cutting depth and wear plays a substantial part in the cutting process [8].

Thus, foreign scholars proposed a new method, rock breaking by conical pick assisted with high pressure water jet [9]. The research on this method has shown that rock breaking by pick assisted with high pressure water jet can reduce the picks load and improve the cutting efficiency of pick. Thus, much research has been conducted on rock breaking by pick assisted with high pressure water jet.

The experimental research aimed both at studying the processes carried out by which mechanical excavation is improved and at quantifying the increment of the excavation performance parameters with water jet [10, 11]. The stone surface treatment with water jets was focused on and it is concluded that the application of water jets in surface treatment enabled obtaining a surface with required roughness while preserving aesthetic appearance of the stone [12, 13]. A Taguchi–fuzzy decision method was used to determine the effective process parameters for improving the productivity of coal cutting by water jet technology [14]. The wear characteristics of the cemented carbide blades in drilling limestone with water jet were studied, which concluded that the wear rates decrease with the increase of the nozzle diameter in the drill bit [15]. The capacity of pulsed water jets was investigated for creating internal breakdown and the relative contributions of the pulse length and pulsation frequency on the surface and subsurface damage caused by a pulsed water jet on rock targets [16, 17]. With the development of water jet technique, the abrasive water jet (AWJ) assistance, as a new kind method, has been developed in hard rock mechanical cutting and drilling [18]. The significant rock properties affecting the recycling of abrasives were investigated in AWJ cutting of granites [19]. The experiments were conducted and compared with the conventional technique, which showed that, with the assistance of abrasive water jet, the drilling depth has increased by about 63%, the thrust force and torque have reduced by about 15% and 20%, respectively [20]. The properties of existing cavitation models were discussed and a compressible mixture flow method was introduced for the numerical simulation of high-speed water jets accompanied by intensive cavitation [21]. Song et al. analyzed the possibility and reasonableness of water jet cutting technology (WJCT) application to rock burst relief and prevention, simulated the distributive characteristics of stress and energy fields suffered by hard coal roadway wall rock and the internal relationships of the fields to the instability, and conducted fields WJCT tests using electromagnetic radiation (EMR) measurement technology [22].

The studies promoted the development and application of conical picks assisted with high pressure water jet, but there were still some shortcomings. One was that pick cutting experiment focused on the effect of different cutting parameters at one water jet configuration, lacking comparative study of different water jet configuration. Another was that the results of experiment were given based on numerical interval instead of exact value. Besides, there were great differences among those conclusions. The third was that it was one-sided to only use the reduction of the cutting force to assess the rock breaking performance assisted with high pressure water jet, which could not reflect the performance comprehensively.

In 2014, four different configuration modes of water jet were firstly presented [23–25], shown in Figure 2. The results showed that the JCP mode was proved the best, followed by the modes of JRP and JFP, and the worst mode was JSP. Thus, the JSP will not be considered any more. And for the JCP, though the best, it is not practical because the nozzle (pick tip) will fail due to severe wear in the rock breaking progress, shown in Figure 3. For the JRP, the nozzle easily interferes with rock in the cutting process; thus a new typed JRP was designed in this paper.

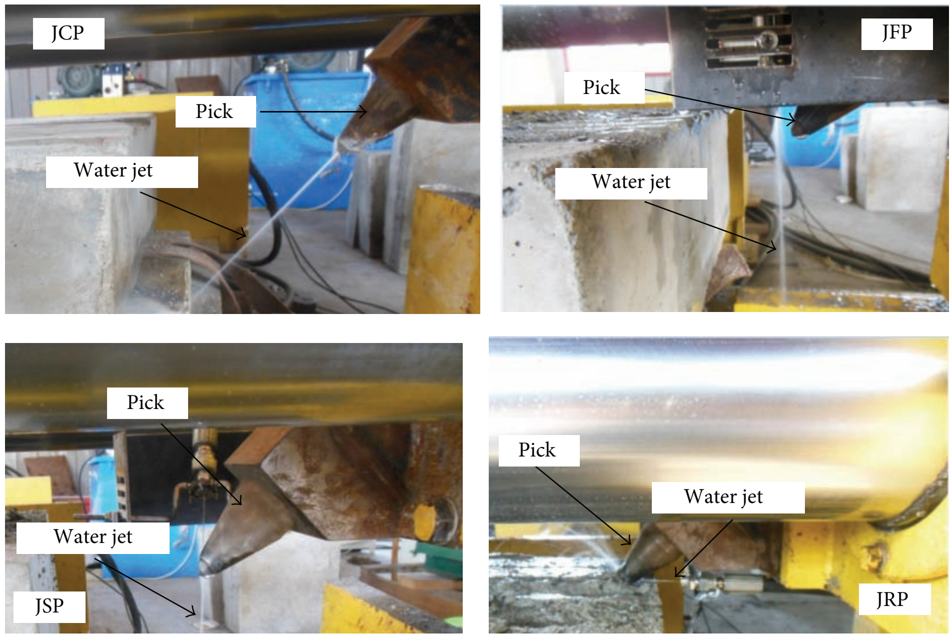


FIGURE 2: Different configuration modes of water jet.

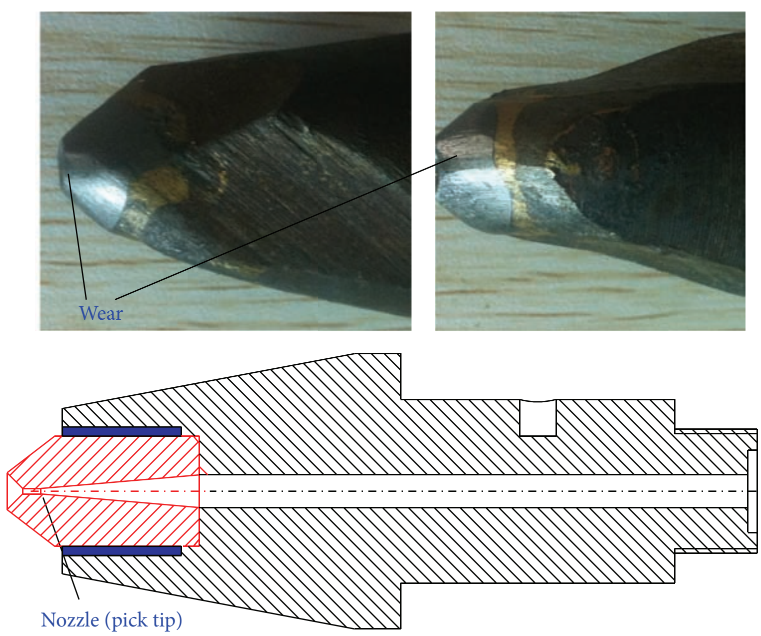


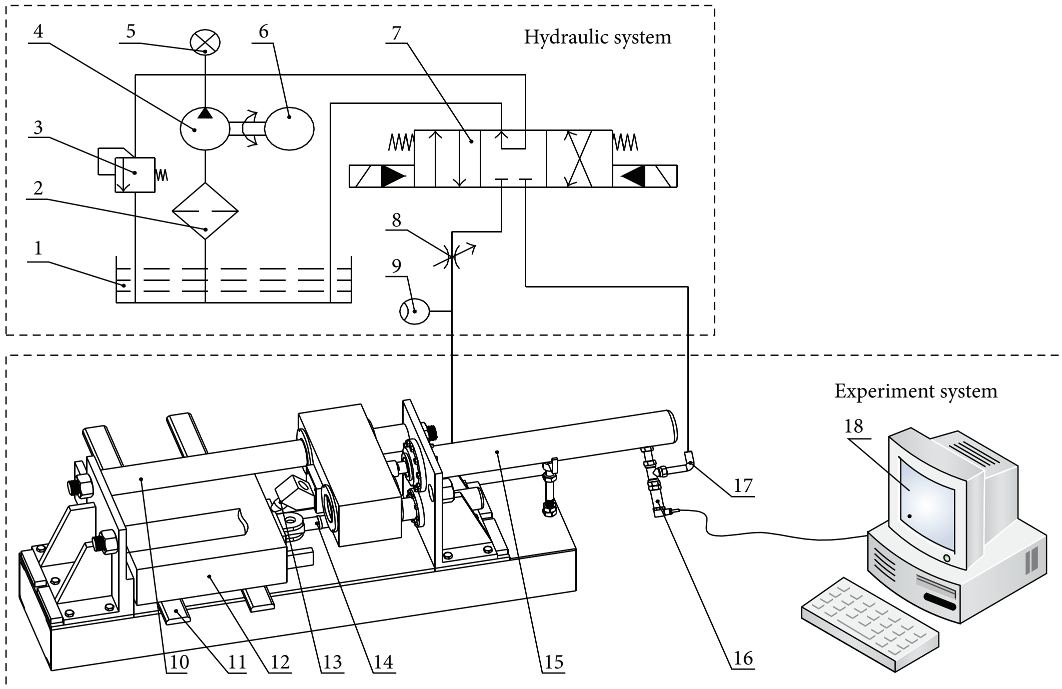
FIGURE 3: Wear of conical pick.

Therefore, based on the analysis of the different water jet configuration's advantages and disadvantages, this paper selects the appropriate jet configuration (JFP, new typed JRP, and the combination one) to conduct the rock breaking experiment to obtain the quantitative results. In the evaluation of rock breaking performance assisted with high pressure water jet, the load fluctuation is included.

2. Experiment Methods

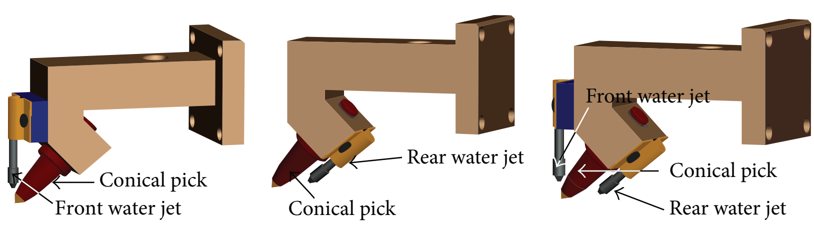
The test bed of rock breaking assisted with high pressure water jet is shown in Figure 4. High pressure oil pump provides power for the clamping cylinder and thrust cylinder. High pressure water pump provides water for the nozzle. The rock sample was clamped on the test bench by clamping cylinder 14. Rock slide 11 can reduce the friction between the rock samples and the test platform, which can conveniently load and move the rock. Pushing cylinder 15 can realize a linear reciprocated cutting action propelling along rail 10. The displacement sensor is used to record the pick's displacement. The pressure sensor is used to monitor and increase the oil pressure to obtain the cutting force.

When designing the pick, the problems such as the determination of cutting angle and the fixing of the nozzle



(1) Oil tank
(2) Oil filter
(3) Relief valve
(4) Pump
(5) Manometer
(6) Motor
(7) Solenoid directional valve
(8) Speed control valve
(9) Flowmeter
(10) Pushing guide rails
(11) Slideway
(12) Rock sample
(13) Cutter
(14) Clamping cylinder
(15) Pushing cylinder
(16) Pressure transducer
(17) Inlet pipe
(18) Computer

Figure 4: The test bed assisted with high pressure water jet.



(a) JFP (b) JRP (c) Combined

Figure 5: Different configuration modes.

should be considered. The cutting angle refers to the acute angle between the pick center line and pick velocity direction. The cutting angle of the pick has a great effect on the rock breaking performance. If the cutting angle is too small, the pressure piece cannot be fully effective. If the angle is too big, the pick tip extrudes the rock severely, which causes a lot of dust and makes the pick wears quickly. Researches show that when the cutting angle is about 45°, the energy consumption is low. Therefore, 45° is chosen as the cutting angle. Different configuration modes are designed, shown in Figure 5. The nozzle diameter is 1 mm.

Cement, sand, and gypsum are used to configure the rock sample in experiments [26]. The external dimension is $600 \times 400 \times 160$ mm. The cylinder rock sample with height of 100 mm and diameter of 50 mm is used to carry out the uniaxial compression test on MTS815.02 testing system. The rock sample's parameters are shown in Table 1. The experimental parameters used are presented in Table 2.

Table 1: Parameters of rock.

Material	Density (kg/m^3)	Elasticity modulus (GPa)	Poisson's ratio	Compressive strength (MPa)
Coal sample	2378	30.12	0.27	12.36

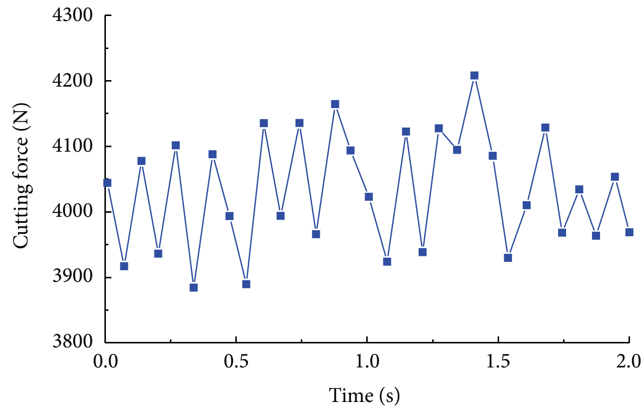


Figure 6: Photo of cutting experiment and cutting force for pick without water jet.

Table 2: Experimental parameters.

Parameter	Value				
Jet pressure (MPa)	0	10	20	30	40
Cutting tool	JFP	JRP	Combined		
Cutting depth (mm)			10		
Cutting speed (m/s)			0.2		
Cutting angle (°)			45		

3. Results and Discussions

In order to compare the effect of different configuration modes, the rock breaking experiment without water jet assistance is carried out firstly. The cutting speed is 0.2 m/s and the cutting depth is 10 mm. Figure 6 shows the photo of cutting experiment and the cutting force of the pick without water jet. The mean cutting force without water jet is 4051 N. The variance is 5713 N^2.

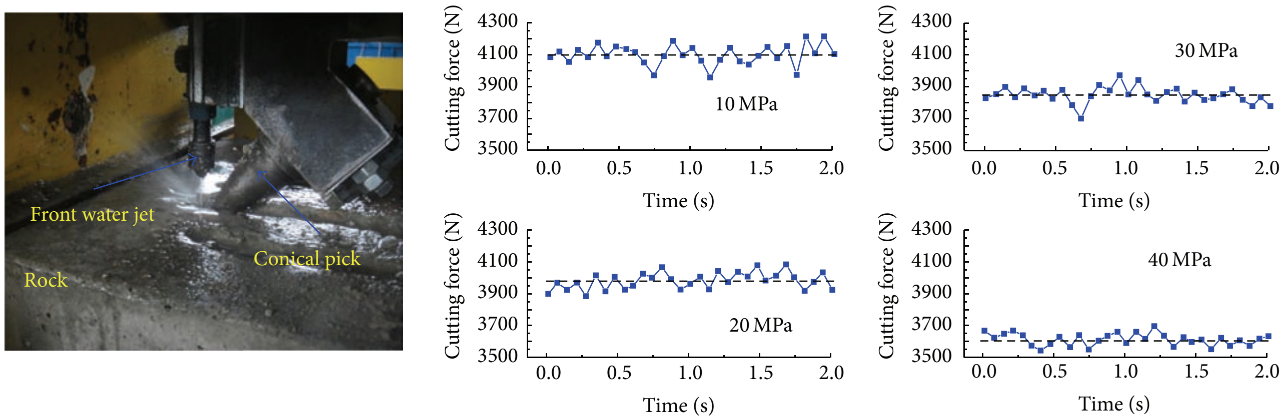
The experiment assisted with high pressure water jet is conducted, the cutting angle is 45°, and the cutting depth is 10 mm. The target distance and the distance between the pick tip and the attack point are 25 mm and 5 mm. The experiment is carried out under the water pressure of 10 MPa, 20 MPa, 30 MPa, and 40 MPa. Figure 7 shows the photos of cutting experiment and the cutting force of JFP and new typed JRP.

The photos in Figure 7 show the picks cutting rock with the assistance of JFP and new typed JRP. The simplified cutting force curves were obtained by filtering the cutting force data tested from pressure sensor. It can be seen that the force value fluctuates around the average and the mean cutting forces of JFP and the new typed JRP decrease with the water jet pressure. To observe the assistance effect of front and rare water jet directly, the force decrease rate was introduced as $\eta = (F_p - F_w)/F_p$, where F_p is the cutting force of a common pick and F_w is the cutting force of pick assisted with water jet. The force statistics decrease rates of JFP and new typed JRP are shown in Figure 8. Moreover, the variance of the cutting force was taken statistics to study the influence of JFP and new typed JRP on fluctuation of cutting force, shown in Figure 9.

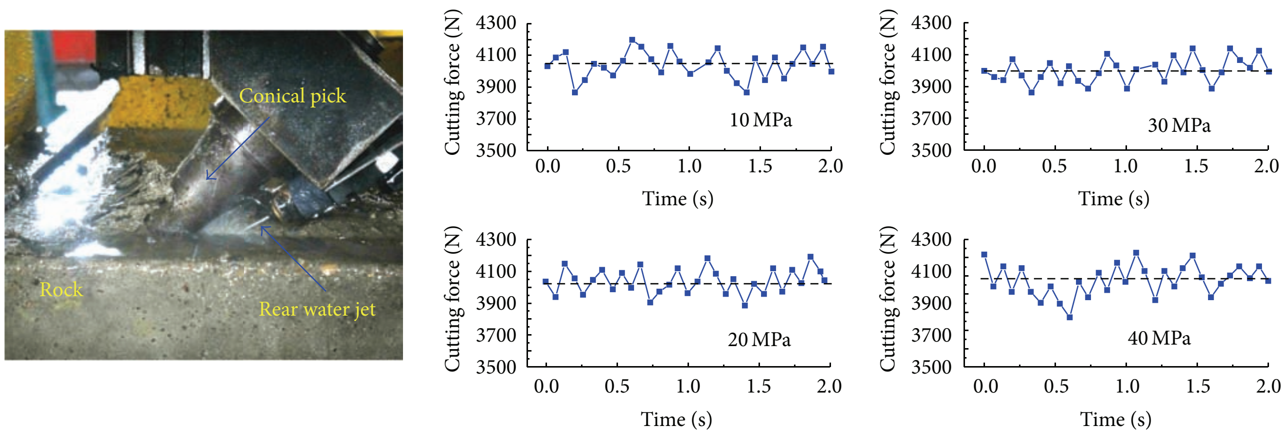
Figure 8 shows that the force decrease rates of JFP and the new typed JRP increase with the water jet pressure. However, the new typed JRP is less effective than the JFP. When the water pressure is 40 MPa, the reduction rate of the cutting force is only 1.86% while it is 10.97% for JFP. The reason is that, firstly, the pick cuts into the rock with an angle (cutting angle), and the jet attack point is far from the pick tip with the influence of the pick holder's shape; the cracks mainly exist in front of pick tip; thus the water jet is hard to go directly into the cracks to extend them further. Secondly, in order to avoid the direct crash between rear nozzle and the rock, the rear jet target distance is large; when the high pressure water erupts, the pressure reduces rapidly, which does not make the best use of the water jet's impact ability.

It should be noted that there is a threshold pressure for the effect of front water jet assistance, and the threshold pressure is about two or two times greater than the coal sample's compression strength. In the above experiment the threshold pressure is around 20–30 MPa. When the water pressure is lower than the threshold pressure, the assistance effect is not obvious, and the force reduction rate is generally lower than 5%. For the front water jet, when the water pressure is lower than 20 MPa, the cutting force even increases. It indicates that, at low pressure, the front water jet cannot timely crush the rock. Instead, a layer of pressure water film is formed on the surface of the rock, which will prevent the rock from caving. In this case, the pick tip's cutting impact cannot perform to the best of its abilities. Moreover, when the water pressure is higher than the threshold pressure, the front jet works better. When the water pressure is up to 40 MPa, the cutting force reduces by 10.97%.

From Figure 9, the variance of cutting force decreases with the water jet pressure generally for both JFP and the new typed JRP. And compared with the new typed JRP, the variance of JFP is smaller. When the water pressure is lower than the threshold pressure, the decrease of load fluctuation is not obvious. It indicates that, at the low pressure area, the water jet mainly plays a role of humidification. The water weakens the rock's frangibility. While the water pressure is higher than the threshold pressure, the water pressure can fully damage the rock and reduce the load fluctuation significantly.



(a) JFP



(b) New typed JRP

FIGURE 7: Photos of cutting experiment for JFP and new typed JRP.

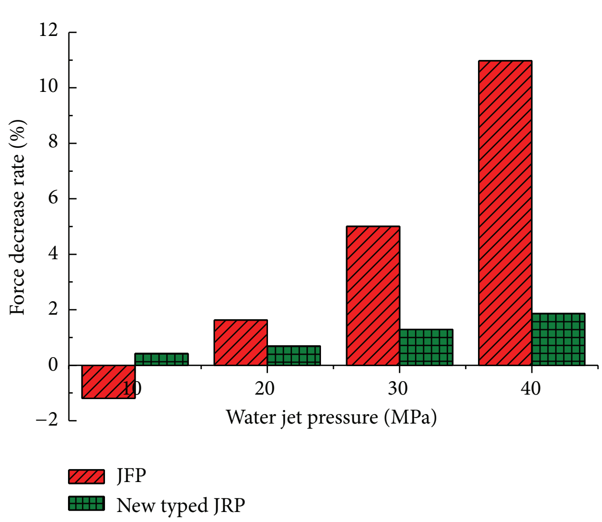


FIGURE 8: Cutting force decrease rates.

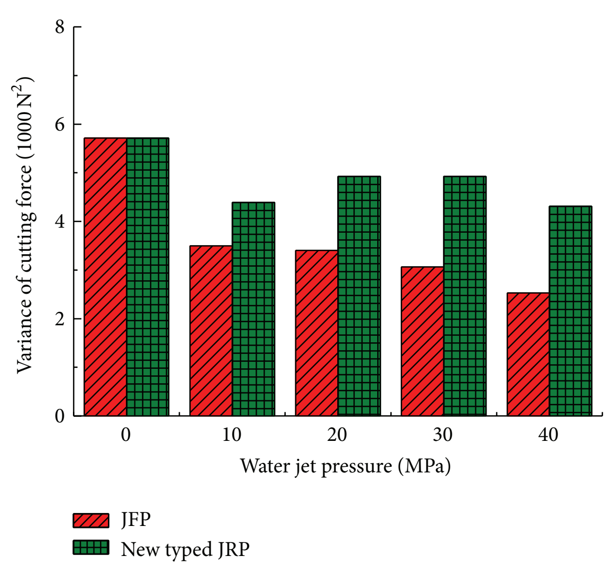
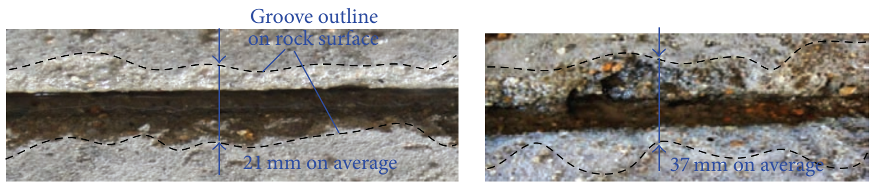


FIGURE 9: Variance of the cutting force.

It should be pointed out that though the assistance effect of rear water jet is not obvious, there are less rock fragmentations behind the pick, so the high pressure water can directly attack the groove to make the cracks extend further. Figure 10(a) shows the groove formed by front water jet of 30 MPa, while Figure 10(b) shows the one formed by



(a) JFP of 30 MPa

(b) New typed JRP of 30 MPa

Figure 10: Grooves formed in the cutting process.

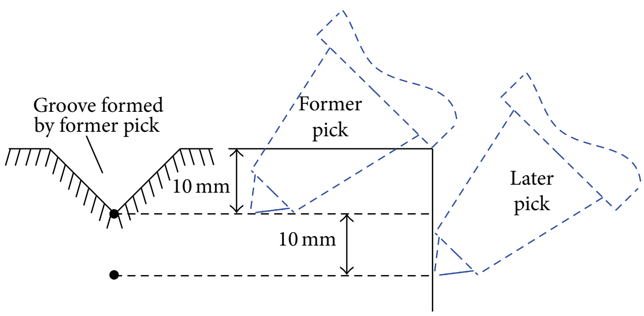


Figure 11: Cutting condition of later pick.

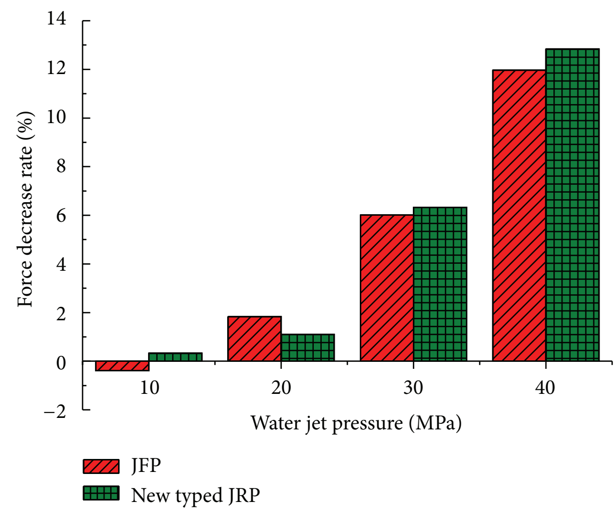


Figure 12: Cutting force decrease rates for later pick.

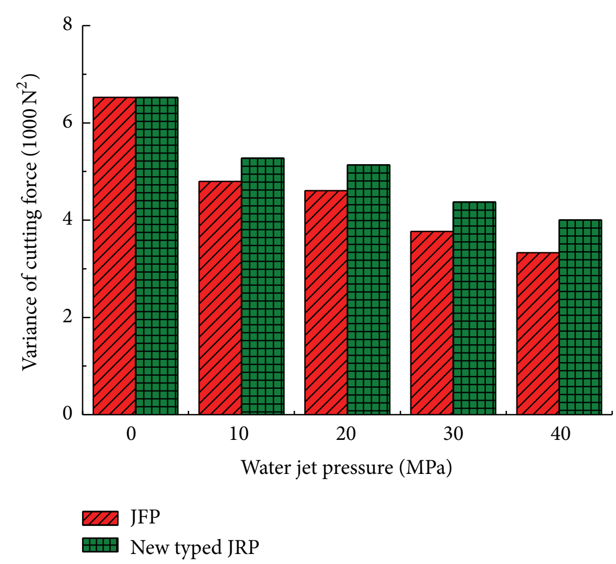


Figure 13: Variance of the cutting force for later pick.

rear water jet of 30 MPa. It can be seen that the groove shape in Figure 10(a) is relatively flat, while the one in Figure 10(b) is broken severely. The broken grooves make preparations for the later cutting. Therefore, the further cutting experiment is necessary to be carried out to explore the influence of groove on rock breaking performance of the later pick.

In order to study the rock breaking performance of the later pick, the further cutting experiment is carried out in the broken groove formed by the 0 MPa, 10 MPa, 20 MPa, 30 MPa, and 40 MPa rear water jet. The cutting depth is 10 mm, shown in Figure 11.

The force statistics decrease rates of the later pick are shown in Figure 12. Moreover, the variance of the cutting force was taken statistics to study the influence of JFP and new typed JRP on fluctuation of cutting force, shown in Figure 13.

Compared with Figure 8, the variation trend and magnitude of the cutting force decrease rate for JFP almost remain the same, while those for new typed JRP increase under different water jet pressure, and the variation trend and magnitude are almost the same as those of JFP. This indicates that there is no difference in influence of the two water jet configuration modes on cutting force decrease rate in the following cutting. Even so, from the experiments data, the new typed JRP is more effective on decreasing cutting force.

Compared with Figure 9, variance of the cutting force in Figure 13, for both JFP and new typed JRP, increases to some degree, which results from the increased interference between rock and cutting pick. But the variation trend and magnitude of variance for JFP almost remain the same; while variation trend for new typed JRP is almost the same as that of JFP, however, the magnitude is larger than that for JFP.

From the analysis above, there is no great difference in influence of the two water jet configuration modes on rock breaking performance. But each has its own advantages; for example, the new typed JRP is more effective on decreasing cutting force and JFP is more effective on decreasing force fluctuation.

Based on the study above, the experiment with combined water jet assistance is conducted to study the rock breaking

Figure 14: Photo of cutting experiment for JFRP.

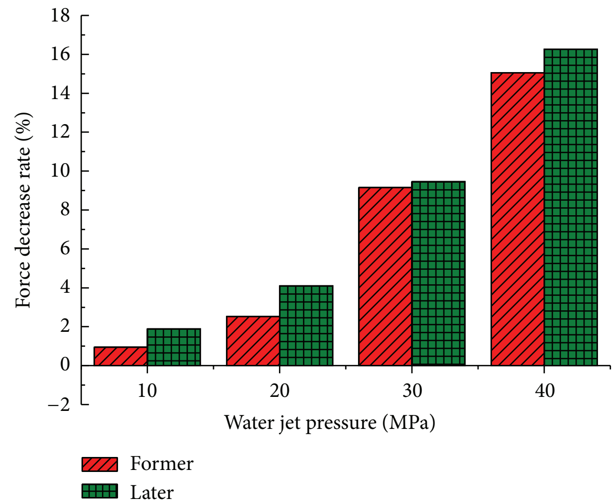


Figure 15: Cutting force decrease rates for combined pick.

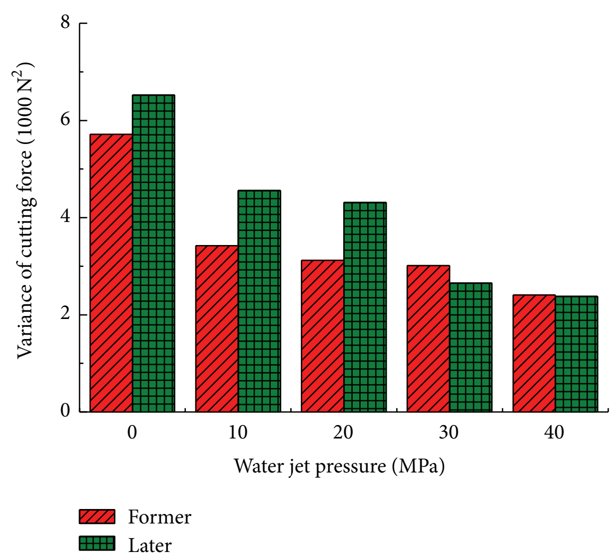


Figure 16: Variance of the cutting force for combined pick.

performance. The combination of those two water jet configuration modes (JFRP) is processed as shown in Figure 14. The experiment conditions are the same as the experiments above. The force statistics decrease rates of the combined pick are shown in Figure 15. Moreover, the variance of the cutting force was taken statistics, shown in Figure 16.

Figures 15 and 16 show that the combination of those two water jet configuration modes (JFRP) is effective for rock breaking. It can both decrease the cutting force and lower down the fluctuation. Compared with that for single water jet configuration, the variation trend of the cutting force decrease rate for the combined one remains the same, but the magnitude increases under different water jet pressure. When the water pressure is up to 40 MPa, the cutting force decreases by 15.06% and the later pick's cutting force can reduce by 16.26%. Under the combined water jet configuration, the cutting force variance decreases significantly, showing that the combined way is helpful to decrease the load fluctuation. This is positive to enhance the picks work stability and prolong the relative parts' service life. But it is important to note that the effect of the combined water jet configuration is not that of the direct adding of JFP and new typed JRP. The injecting off distance increases and the assistance ability decreases when a layer of rock was broken by water jet. At this time, the rock breaking performance will not be enhanced, though the pick is assisted with the combination of those two water jet configuration modes. Thus, the combined water jet should not be applied due to much water and energy waste.

4. Conclusions

(1) The force decrease rates of JFP and the new typed JRP increase with the water jet pressure. However, the new typed JRP is less effective than the JFP. When the water pressure is 40 MPa, the reduction rate of the cutting force is only 1.86%, while it is 10.97% for JFP.

(2) The variance of cutting force decreases with the water jet pressure generally for both JFP and the new typed JRP. And compared with the new typed JRP, the variance of JFP is smaller.

(3) For the later pick, there is no great difference in influence of the two water jet configuration modes on rock breaking performance. But each has its own advantages; for example, the new typed JRP is more effective on decreasing cutting force and JFP is more effective on decreasing force fluctuation.

(4) The combination of those two water jet configuration modes (JFRP) is effective for rock breaking. It can both decrease the cutting force and lower down the fluctuation. Compared with that for single water jet configuration, the variation trend of the cutting force decrease rate for the combined one remains the same, but the magnitude increases under different water jet pressure. When the water pressure is up to 40 MPa, the cutting force decreases by 15.06% and the later pick's cutting force can reduce by 16.26%. However, the effect of the combined water jet configuration is not that of the direct adding of JFP and new typed JRP. Thus, the combined water jet should not be applied due to much water and energy waste.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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