

Study on the Theory of High Pressure Water Jet Coal Breaking and Its Main Controlling Factors

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Abstract. In order to solve the problems of gas extraction and pressure relief and permeability enhancement under low permeability and high surrounding rock stress conditions in deep coal seams, the ultra-high pressure hydraulic cutting technology is proposed. The mechanical mechanism of coal breaking by high pressure water jet is analyzed. The process of coal breaking by jet is divided into stress wave effect and secondary crack propagation effect. The effects of physical and mechanical properties of coal and rock and jet parameters on jet cutting depth are analyzed theoretically. The results show that the shear strength, tensile strength, fracture and pore development degree of coal and rock correspond to different types of coal and rock failure. With the increase of jet pressure and flow rate (nozzle diameter), the jet cutting depth increases gradually. The influence of jet rotating speed on cutting depth is analyzed. It is concluded that reducing rotating speed should be adopted to improve cutting depth in field practice. The research results can effectively improve the stress state of coal body, play the role of pressure relief and permeability enhancement, and improve coal seam permeability and gas release capacity, which can well meet the control needs of coal mine gas complex dynamic disasters.

1. Introduction

The mining depth of coal mines in China extends to the depth at the rate of 10m~30m per year. The mining coal seams show remarkable characteristics of "low coal seam permeability, high surrounding rock stress and high coal seam gas pressure". Faced with the complex dynamic disasters of coal and rock in deep mines, it is difficult to achieve ideal extraction effect under the conditions of high surrounding rock stress and low permeability by adopting single measures such as surface well or borehole pre-pumping. It is unable to eliminate the elastic strain energy accumulated in coal and rock and reduce the stress threat in the inland of mining area. The effective pressure relief and permeability enhancement measures are needed to meet the needs of the treatment of composite power disasters. It is the direction of joint efforts of coal mine scientific researchers to study a technical means which can not only meet the requirements of rapid gas extraction, but also reduce the stress of coal seam [1]. Water jet cutting technology is to cut coal seam with high pressure water as technical means, and man-made fissures as gas flow space to improve the gas flow state in coal seam and create favorable conditions for extraction. It is an important development direction of prevention and control of coal and rock composite dynamic disasters in coal mine [2].

As a new technology developed rapidly in recent years, ultra-high pressure hydraulic slotting technology is suitable for cleaning, drilling, cutting and rock breaking, which reduces costs and improves work efficiency. The technology of pressure relief and permeability enhancement by high-



pressure hydraulic drilling is to use water as power to scour and strip the coal around the borehole and increase the fissures in the coal [3-5], which can greatly improve the gas flow state in the coal seam, create favorable conditions for gas extraction, change the original stress and fissure state of the coal body and reduce the stress in the coal body and surrounding rock. Force can not only weaken or eliminate the power of outburst, but also greatly change the physical and mechanical properties of outburst coal seam, play the role of pressure relief and outburst prevention, and improve the permeability and gas release capacity. It is one of the effective measures to prevent and control gas dynamic disasters in coal mines.

2. Mechanics Mechanism of Coal Breaking by High Pressure Water Jet

The velocity and direction of jet impacting on coal wall change dramatically and the distribution of impact load is complex. With the increase of cutting depth, the coal wall in the impacting area will be destroyed. On the one hand, the restriction conditions of flow field change, which affects the velocity distribution inside the jet, on the other hand, changing the force of jet on coal and rock will cause the jet edge to be destroyed. The boundary conditions have changed further, so the mechanism of coal seam cutting by water jet has not yet formed a mature and perfect theoretical system. At present, the accepted hypothesis divides the process of coal breaking by water jet into two stages: water hammer pressure and stagnation pressure, which correspond to the stress wave effect and crack propagation effect of water jet respectively. According to the characteristics of soft coal seam through drilling, the best effect of strengthening pumping is the high pressure water discharge and increase penetration technology. The technique of water jet pressure reduction is mainly used to cut and flush the coal around the borehole to form a large area of pressure relief and penetration in the borehole to achieve the purpose of increasing the permeability. The impact process of high pressure water jet shown in Figure 1.

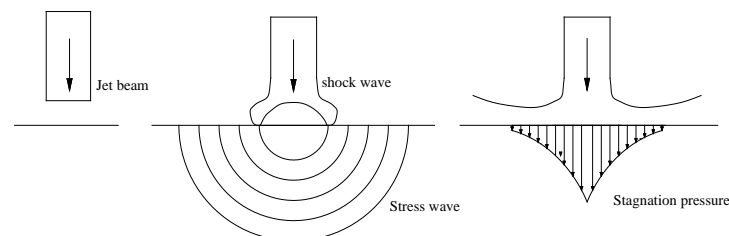


Figure 1. Impact Process of High Pressure Water Jet

2.1. Stress Wave Effect

The main body of coal and rock damage caused by water jet is the water hammer pressure stage in the first few microseconds. When the jet first contacts the surface of coal and rock, the reaction force of coal and rock to the jet transfers deformation in the center of the jet, and the deformation in the compressed area forms in the jet. The propagation velocity in the coal is faster than that in the jet, which produces water hammer pressure. When the jet liquid column contacts coal and rock sufficiently and the jet flow field is rebalanced under the external restraint, the impact of the jet decreases from the water hammer pressure to about one tenth of the stagnation pressure. In this process, the impact effect in a very short time makes the coal and rock in a compressive state. Because of the sharp decrease of the compressive stress, the coal and rock in a highly compressive state are rapidly released to form a tensile load. When the tensile stress produced by the unloading exceeds the strength limit of the coal and rock itself, the failure occurs. Because of the entrainment effect of the jet boundary layer, the axial velocity center of the jet is larger and the edge is lower, so the elastic strain energy at the impact edge of the jet is released most sufficiently, and the damage first occurs in the region. With the destruction of coal and rock at the impact edge, the coal body with strong

compression at the jet center expands along the radial direction, and the coal body damage area expands from outside to inside.

2.2. Secondary Crack Propagation Effect

Coal and rock are typical porous media materials. Before water jet impingement, there are micro-structural defects such as pore, fracture and bedding. Under the impact of water jet, cracks in coal and rock mass develop and propagate, and eventually penetrate with the free surface to separate the coal block from the coal and rock surface as a whole. Crack propagation under water jet impingement is shown in Figure 2.

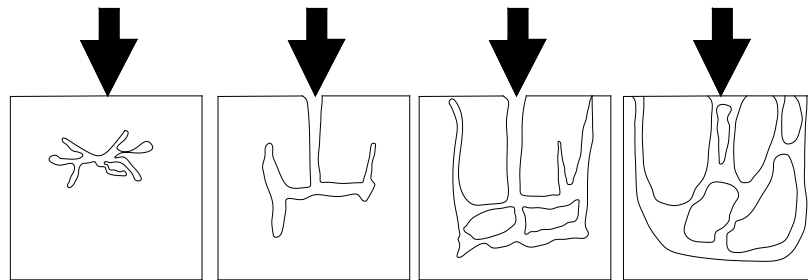


Figure 2. Crack Propagation under Waterjet Impingement

According to the different mechanism of crack development, there are two different types of failure: one is that the damage effect is caused by the direct impact force of the jet, the jet impact produces the tensile stress zone in the coal and rock, the tensile action forms the radial crack, the crack propagates in the radial direction, and with the crack expansion, the impact pit is formed. Another kind of damage effect is caused by water wedge. In the process of water jet impact, high-pressure water propagates along the crack and produces stress concentration at the crack tip. The crack destroys coal and rock mass under hydrostatic pressure.

2.3. Jet Erosion Effect

Coal and rock mass are heterogeneous materials. The structural characteristics of plants and geological processes in coal-forming process will destroy the integrity of coal and rock, reflecting the random distribution characteristics of coal and rock strength. Under the impact of high-pressure water jet, some coal-rock units with higher strength can resist the erosion and destruction of jet. The lower strength part falls off from the surface of coal-rock under the action of water erosion, and then the overall strength of coal-rock is weakened. With the increase of jet pressure, the number of separated coal-rock units increases gradually, and the stability of the higher strength part is affected, which is taken away by jet under impact.

3. Effect of Physical and Mechanical Properties of Coal on Jet Cutting Depth

3.1. Effect of Coal Mechanics Strength of Coal on Jet Cutting Depth

In the process of high pressure water jet impacting on coal body, under the action of the axial compression of the jet, the coal body displaces downward, and the core area of impacting and the edge area produce relative dislocation. From the impact edge area to the unaffected area, the radial displacement of coal and rock near the axis caused by the axial settlement results in tensile deformation far away from the impact position of the jet. As a kind of rock material, the compressive strength of coal and rock is far greater than the shear strength and tensile strength. When the axial impact pressure of jet is still lower than the compressive strength of coal, the shear stress in coal and rock exceeds the limit of shear strength due to the mechanical characteristics of brittle material of coal and rock, which leads to the relative occurrence of coal and rock at the impact axis position. Distortion

or the tensile stress exceeds the ultimate tensile strength, which results in tensile fracture of coal and rock far away from the impact zone.

3.2. Effect of Coal Cracks on Cutting Depth

The influence of coal-rock fracture development on cutting depth includes two aspects. The stress wave generated during the initial impact process of jet reflects when it encounters cracks. Therefore, it is advantageous for jet to break coal body by limiting the propagation range of stress wave and increasing the unloading intensity of stress wave. On the other hand, when the jet impinges on the coal body stably, the high-pressure water is transmitted to the tip of the coal body through the cracks to produce the water wedge effect, which makes the cracks continue to expand and finally cause the macro damage in the coal body. Therefore, when the slotting pressure is low, the jet flow rate is large and the slotting time is long, the stress wave effect produced by the lower jet impact velocity is not significant. The long-term impact of the jet makes the high-pressure water have enough time to make the coal body continue to crack and expand. The coal breaking by jet mainly depends on the secondary crack propagation effect. When the cutting pressure is high, the jet flow is small and the cutting time is short, the stress wave propagation is limited by the development of the fracture, and the stress wave relief strength is enhanced. The jet coal breaking mainly depends on the stress wave effect.

4. Effect of Jet Parameters of Coal on Cutting Depth

4.1 Effect of Pressure and Flow Rate of Coal on Cutting Depth

4.1.1. Effect of Jet Pressure

The water jet pressure determines the velocity of water jet and is the most important parameter affecting cutting ability. Practice has proved that there is a threshold pressure when water jet impacts coal and rock. Coal and rock under the threshold pressure only produces plastic deformation and hardly destroys. Coal and rock will produce leap-forward failure when it is higher than the threshold pressure. For plunger pumps, the greater the static pressure in the high-pressure cylinder liner, the greater the initial jet velocity at the nozzle outlet. The force acting on coal and rock under stable impact is expressed in the form of jet flux. The increase of jet flux makes the load on the surface of coal and rock increase when the direction of jet velocity is changed, and then the jet cutting depth increases.

4.1.2. Effect of Jet Flow Rate of Coal on Cutting Depth

The water jet flow rate is determined not only by the jet velocity, but also by the jet volume flow rate. According to Bernoulli equation, when the pump output power is enough, the jet velocity is only related to the pump pressure. The larger the nozzle diameter is, the larger the jet volume flow is at the same water jet velocity. Whether in the first stage or the second stage of slotting process, the main factors, such as water hammer pressure and stagnation pressure, are affected by jet flux. Therefore, the larger the nozzle diameter, the stronger the slotting ability of the jet.

4.2 Effect of Rotating Speed on Cutting Depth

The rotational velocity of high-pressure water jet has three main effects on the cutting depth: changing the stress state on the surface of coal and rock mass, reducing the water cushion effect in the cutting process, and reducing the impact time of the jet on the unit area.

The stress state of coal and rock mass surface under the impact of rotating jet is changed. The stress state of coal and rock mass surface under the impact of rotating jet is changed. The rotation of jet produces tangential force along the surface of coal and rock mass besides the vertical force perpendicular to the surface of coal and rock mass. Compared with the simple axial impact on coal mass, the axial shear force along the slot greatly improves the rock breaking efficiency of jet. Secondly, the jet rotation makes the direction of inflow and reflux different, which reduces the water cushion effect in the slotting process. Because the dynamic viscosity of water is much larger than that

of air, the attenuation of jet velocity in water is more severe, so the weakening of water cushion effect improves the cutting ability of jet. Finally, the increase of jet rotation speed reduces the cutting time of coal in unit area. Because the continuous propagation of internal cracks in coal is a dynamic process, the reduction of cutting time will stop the development of the expanded cracks due to the disappearance of external loads. In summary, coal with higher hardness coefficient and worse fracture development, higher rotation speed is conducive to changing the stress state on the surface of coal body and increasing the depth of coal breaking; coal with lower hardness coefficient and fully developed cracks, higher rotation speed is not conducive to the re-expansion of internal cracks in coal body and thus the overall separation and decline. Low coal breaking depth.

In practice field, coal and rock are affected by geology and excavation stress. Usually, the strength of coal and rock is low and there are many internal micro-structures. For a jet with cutting pressure up to 100MPa, the exit velocity of nozzle is 447m/s, and the rotation speed of drilling rig is about 40r/min~180r/min. The radial velocity is about 0.6m/s. Therefore, in practice field, it should be adopted. Reduce the rotation speed to increase the cutting depth.

5. Mainly Conclusion

(1) In terms of physical and mechanical properties of coal and rock, the main factors affecting jet cutting depth include shear strength, tensile strength, fracture and pore development, which correspond to different failure types of coal and rock respectively. The corresponding failure mechanism of shear strength is shear slip failure of coal and rock surface, the corresponding failure mechanism of tensile strength is transgranular fracture of coal and rock interior, and the corresponding failure mechanism of pore and fracture is secondary propagation of cracks in coal and rock interior.

(2) In terms of jet properties, the main factors affecting jet cutting depth include: jet parameters and jet rotation speed, jet parameters affecting high-pressure water jet flux, thereby affecting the impact of jet on coal and rock, the rotational velocity of jet mainly eliminates the water cushion effect in rock breaking by jet, affects the time when coal and rock are impacted by jet in unit area, and changes the size and direction of jet impact force.

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