applied sciences

MDPI

Review

A Review of Selected Solutions on the Evaluation of Coal-Rock Cutting Performances of Shearer Picks under Complex Geological Conditions

Linlin Wang [1,2,*], Dekun Zhang [3], Dagang Wang [4] and Cunao Feng [3]

[1] Carbon Neutrality Institute, China University of Mining and Technology, Xuzhou 221008, China
[2] Jiangsu Key Laboratory of Coal-Based Greenhouse Gas Control and Utilization, Xuzhou 221008, China
[3] School of Materials and Physics, China University of Mining and Technology, Xuzhou 221116, China
[4] School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou 221116, China
* Correspondence: linwang@cumt.edu.cn

Abstract: During automatic and intelligent cutting at the coal mining face, complex geological conditions (fold structure, fault structure and magmatic intrusion) easily cause distinct occurrence conditions of coal rock seams (gangue, inclusion, or fault in the coal and rock), which induces different coal-rock cutting performances of shearer picks. Therefore, the objective of the present study is to review the selected solutions on the evaluation of coal-rock cutting performances of shearer picks under complex geological conditions. Occurrence conditions of coal rock seams were classified according to different criteria. Mechanical coal-rock breakage of coal rock by shearer picks were introduced. Shearer pick forces during coal-rock cutting (load spectrums of the pick and the mechanical model of the pick force) and coal-rock cutting mechanism (coal-rock cutting process by the pick and pick failure mechanisms) were discussed. The service safety evaluation of the pick based on wear and fatigue (pick wear, quantitative evaluation of service safety, and methods to improve the service safety) was presented. Finally, research prospects were outlined to propose the future research focus of shearer picks under complex geological conditions, such as the adaptive cutting of shearers, the fusion detection method of coal-rock interface by automatic shearers, the effects of geological conditions on coal-rock cutting mechanisms, the selection of systems suitable for different geological conditions, and shearer pick reliability evaluation. Results of this study are of great significance in understanding failure modes and the cutting mechanisms of shearer picks, quantitatively evaluating pick safety, promoting the automatic and intelligent cutting of coal rock seams, and thereby improving the production efficiency of shearers.

Keywords: shear; picks; geological conditions; coal-rock cutting

check for updates

Citation: Wang, L.; Zhang, D.; Wang, D.; Feng, C. A Review of Selected Solutions on the Evaluation of Coal-Rock Cutting Performances of Shearer Picks under Complex Geological Conditions. *Appl. Sci.* **2022**, *12*, 12371. https://doi.org/10.3390/app122312371

Received: 2 November 2022
Accepted: 28 November 2022
Published: 2 December 2022

1. Introduction

The shearer is an important piece of equipment at the fully mechanized coal mining face (Figure 1). The pick is the core component of the cutting unit as the key device of the shearer [1,2]. During automatic and intelligent cutting at the coal mining face, the complex geological conditions, such as the fold structure, fault structure and magmatic intrusion, induce distinct occurrence conditions of coal rock seams (gangue, inclusion, or fault in the coal and rock), and the difficulty in the identification of complex coal-rock interfaces at the coal mining face [3–5]. Complex occurrence conditions, shearer vibration, rotary cutting of the helix drum and uneven track will cause the wear deterioration and even fracture of the pick when cutting the coal wall [6,7], which greatly affects the safety and reliability of the pick, service life of the drum and production efficiency of the shearer. Therefore, it is essential to master occurrence conditions of coal rock seams, mechanical coal-rock breakage by shearer picks, shearer pick forces during cutting, the coal-rock cutting mechanism and service safety evaluation of the shearer pick. However, the correlations between complex geological conditions and wear deterioration/safety and reliability evaluation of shearer picks have not been reported yet. The reviews on the cutting loads, cutting mechanisms, quantitative evaluation of wear deterioration and service safety evaluation of shearer picks are of great significance for establishing the wear deterioration evaluation system of shearer picks and obtaining the influencing factors of wear deterioration of shearer picks. Meanwhile, research results can promote automatic and intelligent cutting of coal rock seams, reduce the equipment fault rate and improve production efficiency of the shearer. However, this article is a comprehensive review of selected solutions on the evaluation of coal-rock cutting performances of shearer picks under complex geological conditions. The results can be applied in cases of the complex geological conditions in countries and regions concerned in the present study.

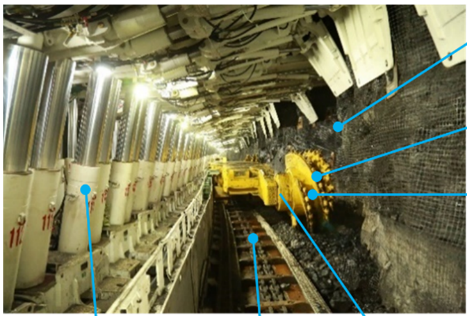

Figure 1. The fully mechanized coal mining face.

The aim of the present study is to present the evaluation of coal-rock cutting performances of shearer picks under complex geological conditions, nevertheless, due to the volume of the article, only the most important solutions published in recent years are presented. Section 2 shows the occurrence conditions of coal rock seams. Mechanical coal-rock breakage of coal rock by shearer picks is introduced in Section 3. In Section 4, the research progress on shearer pick forces during coal-rock cutting is presented. Section 5 exhibits the coal-rock cutting mechanism. The service safety evaluation of the pick based on wear and fatigue is reviewed in Section 6. Finally, the research prospect is proposed in Section 7.

2. Occurrence Conditions of Coal Rock Seams

Occurrence conditions of coal rock seams at the coal mining face are affected by geological structure conditions. In the case of folded structures, coal rock seams are compressed due to plastic deformation of strata and exhibit the wavy bending, which results in the coal seam thickness change locally. As the geological condition is a fault structure, the fault of a coal rock seam induces the discontinuity of mining operation. However, the geological condition of magma intrusion reduces the thickness of the coal seam and increases its hardness, which hinders the continuity of shearer operation [8].

In general, occurrence conditions of coal rock seams are composed of whole coal and whole rock (through the fault) as well as coal and rock mixtures (coal and roof, coal and floor, coal and gangue, coal and inclusions) [9]. The roof and floor strata are located above and below the coal seam, respectively; complex coal seams show at least 1–2 layers of stable gangue strata, and several layers at most (Figure 2) [10]. In China, there are lots of coal bases and mining areas which exhibit distinct geological occurrence conditions of coal seams as shown in Table 1. According to coal seam thickness, the coal seam can be divided into thin coal seam (<1.3 m), medium thick coal seam (1.3–3.5 m) and thick coal seam (>3.5 m). According to the standard GB/T 18023-2000 in China, the coal is macroscopically divided into bright coal (vitreous and bright coal > 80% and presence of metallic or metal-like luster), semi-bright coal (vitreous and bright coal 50–80% and presence of glass luster), semi-dark coal (vitreous and bright coal 20–50% and presence of dull luster) and dull coal (vitreous and bright coal < 20% and presence of silk luster). However, there are lots of classification methods of coal lithotype according to different criteria (Table 2). Li et al. [11] revealed that hard dirt bands are mostly distributed about 0.34 m away from the roof with a thickness of 0~0.4 m, of which 71% exhibits the thickness of 0~0.2 m and 21% presents the thickness of 0.2~0.4 m. They are distributed unevenly in layers. Generally, areas with hard dirt bands smaller than 0.2 m can be directly mined by the improved powerful drum-reinforced pick shearer. Areas with hard dirt bands thicker than 0.2 m need to be blasted. Krivosheev and Koval [12] employed the instrument for recording acoustic signals on tape and their subsequent analysis, to obtain a "map" of seam inclusions. Ordin et al. [13] developed the model of a coal seam with distributed geological and geomechanical characteristics using inverse distance weighting, and found the hyperbolic dependences of the drum shearer advance speed and capacity on the coal seam thickness.

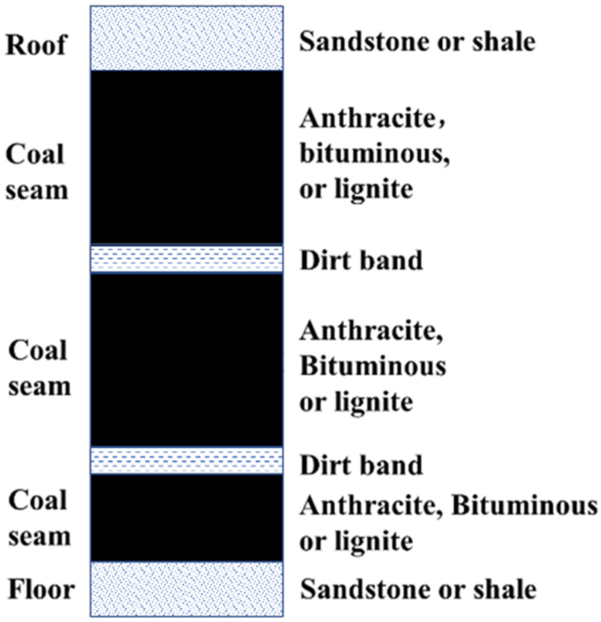

Figure 2. Geological occurrence conditions of coal rock.

Table 1. Geological occurrence conditions of coal seams at different coal bases and mining areas.

Mining Area	Coal Base	Geological Occurrence Conditions of Coal Seams
Jiaozuo	Henan	Large coal seam thickness and stable distribution indicating simple structure coal seam [14]
Hancheng	Huanglong	Strong in the east and south, weak in the west and north, complex in the edge shallow region, and simple in the middle deep region [15]
Huaibei	Lianghuai	Large coal seam thickness, unstable distribution and complex geological occurrence conditions [16]
Shendong	Shendong	Large coal seam thickness, good geological occurrence conditions, simple hydrogeological, engineering, and environmental geological conditions of coal seams [17]
Yushen	Shanbei	Stable coal seam layer, simple structure, great variation of individual coal seam thickness [18]
Shengli	Mengdong	Lots of coal seams, large thickness, high coal bearing ratio, shallow buried depth and good continuity [19]
Shizuishan	Ningdong	Lots of coal seams, large thickness, stable coal seam distribution, medium complex geological structure, gentle formation occurrence [19]

Table 2. Classification of coal lithotype.

Scholar/Institute	Country	Classification Criteria	Coal Lithotype
Stopes MC [20]	UK	Macroscopic appearance of coal strip	Vitrinite, bright coal, dark coal and silk coal
Diessel [21]	Australia	Ratio of bright strip to dull strip in coal	Bright coal, strip bright coal, strip coal, strip dull coal, dull coal and fibrous coal
Renton [22]	USA	Ratio of bright strip in coal	Bright coal, duroclarain, clarodurain, dull coal
ASTM [23]	USA	Coal shape and macroscopic appearance of strip	Strip coal (vitrain, dull coal, fusain), non-strip coal
Thyssen Mining [24]	Germany	Coal shape and average brightness	Strip coal (bright coal, semi-dull coal, dull coal), non-strip coal
Standardization Administration [25]	China	Average gloss degree and content of bright component of coal	Bright coal, semi-bright coal, semi-dull coal, dull coal

3. Mechanical Coal-Rock Breakage of Coal Rock by Shearer Picks

The mechanical coal-rock breakage indicates the direct breakage of coal rock by shearer picks [26]. The picks are installed in pick holders, furnished on the cutting head's lateral surface, and together form a system of picks. The rotary mounting of picks in the holders enables their stochastic rotation and symmetrical wear [27–29]. If certain conditions related to cutting angles are not obtained, the picks are blocked in the holders, and their wear is asymmetrical [30–34]. During the selection of design parameters of the picks and holders, we have to consider geometrical and kinematic parameters of cutterhead and cutting machine [30]. Meanwhile, the mining and geological conditions must be considered, particularly the mineral's properties (cutting resistance, abrasivity) [35–39]. In order to ensure the premised cutting efficiency and costs, Krauze et al. [31] thought that conical picks should be used. Conical picks are used in cutting heads due to their excellent durability, greater than radial or tangent picks. The pick body is a solid of revolution consisting of working and handle parts [29,40]. The working part is equipped with a WC-Co insert, i.e., a pick tip [41–45]. The quality of conical picks is related to their construction (cutting angles, dimensions), material parameters of the pick body (chemical composition, hardness, microstructure, steel grade), and pick tip (dimensions, HV30 hardness, density, chemical composition-determination of the mass fraction of carbide phase (%WC), matrix (%Co) and WC grain size).

Different mechanical coal-rock breakage equipment presents distinct pick types, layout modes and output powers. Bakhtavar [46] determined the optimum drum shearer for Tabas mine using decision making process. Ivanov and Ivanova [47] thought that variations in the level of seismo-acoustic activity of the seam reflected variations in the state of stress of the seam close to the face. From the comparison of the mechanical coal-rock breakage methods of Hob, diamond core drilling, drag bit and impact grinding [48], it is clearly seen that the impact grinding method exhibits good coal-rock breakage properties. As the drum shearer pick directly acts on the coal-rock, it presents a small contact deformation area at first, then the crack initiation at the stress concentration region below the pick occurs, afterwards the unstable crack propagation of the main crack, and finally the formation of falling coal-rock debris [49,50]. In order to explore the mechanical coal-rock breakage mechanism, previous researchers have proposed theoretical cutting models [51–54] and finite element models. Meanwhile, discrete element models of pick cutting coal rock have been established to investigate the evolution of pick force versus cutting depth, chip formation at the leading edge of the pick, and crack initiation around the pick [55–57]. Besides, Balci et al. [58] have established the full-size single-pick coal-rock cutting machine at the Istanbul University. Bakar and Gertsch [59] have established the linear coal-rock cutting machine at the University of Missouri. Li [32] from China University of Mining and Technology have established the full-size single-pick coal-rock cutting machine. Detailed illustrations of progress on the pick cutting coal rock can be found in Table 3.

Table 3. Research progress on the pick cutting coal-rock.

Methods		Scholar	Research Contents
Theory	Tensile stress	Evans	Cutting mechanics model of pick based on tensile stress [51]
	Shear fracture failure	Nishimatsu	Cutting mechanics model of pick based on maximum shear stress [60]
	Brittle tensile failure	Xue	Cutting model of pick cutting soft rock [61]
	Evans model	Wang	Calculation model of peak cutting force under symmetrical and asymmetric truncation conditions [54]
Finite element	LS-DYNA	Menezes	Finite element model of pick cutting coal rock [62]
	ANSYS	Raghavan	Effect of cutting angle on coal-rock stress distribution and dust capacity [63]
	ABAQUS	Guan	Effects of inclination angle parameters on pick force evolution [64]
	MTALAB/ANSYS	Ji	Evolutions of the velocity, acceleration and force of pick [65]
Discrete element	Object ARX+ AutoCAD	Cao	Effect of cutting angle on the speeds of coal particles at the pick front, caving mode and fracture failure characteristics of coal rock [66]
	EDEM	Zhang	Effects of structural and kinematic parameters of the drum on the pick cutting performance and optimization design of drum structure [67]
	PFC	Liu, Mendoza and Gvan	Effects of pick type, cutting depth, traction speed and angular speed of drum on cutting speed, specific energy consumption, crack initiation and propagation during pick cutting coal rock [9,68,69]
Experiment	Coal-rock cutting by an individual pick	Liu and Wang	Effects of physical parameters of coal rock, cutting depth, installation angle of pick on specific energy consumption, pick tip temperature and pick cutting force [53,70]
	Full-size shearer pick cutting tests	Li	Pick cutting force and drum torque in cases of different cutting conditions [32]
	Linear cutting tests	Bakar, Balci and Bilgin	Effects of the type and physical properties of coal rock, cutting depth and speed on acoustic emission characteristics, cutting force and specific energy consumption during pick cutting coal rock [59,71–74]

4. Shearer Pick Forces during Coal-Rock Cutting

4.1. Load Spectrums of the Pick

When the shearer drum cuts the roof and floor, the occurrence of coal rock seam is directly related to the magnitude, direction and action location of the drum load. The cutting force will increase suddenly when the drum cuts the roof, floor or dirt band. When analyzing the drum load, the cutting direction of the pick presents a certain angle with the bedding of coal rock, which changes with the rotation. The position of the dirt band and its influence degree are considered, that is, the angle between the cutting force direction and the bedding varies with the position of the dirt band. Therefore, load spectrums of the drum and pick can demonstrate the cutting state and accurately identify the state of cutting coal rock, i.e., cutting the roof or the floor. Quantitative evaluations of cutting performances under different geological conditions and distinct cutting conditions are of practical significances for autonomous control, optimizations of cutting trajectory and working parameters, and improvement of productivity and work safety. Cui [75] focused on the quantitative descriptions of different geological and cutting conditions, and established the complementary relationships between geological conditions/cutting conditions and cutting performance/sensor sensing parameters, which improved the accuracy and reliability of prediction and correction. He described the cutting load and direction of coal rock in cases of the drum cutting different roof and floor, dirt band and bedding states, through the coal-rock identification associated load characteristic model. He also proposed the load magnitude and direction characteristics, and dynamically monitored the difference of vibration and noise under different coal-rock occurrence conditions.

When the shearer drum cuts the roof and floor, the occurrence states of coal-rock strata are directly related to the amplitude, direction and action point of the drum load. The cutting pressure will increase suddenly when the drum cuts the roof, floor or dirt band. When analyzing the drum load characteristics, the pick cutting direction presents a certain angle with the bedding and changes continuously with the rotation. Considering the locations of dirt band and its influence degree, the angle between cutting force direction and the bedding varies with the dirt band location. Therefore, the exploration of load amplitude frequency characteristics of the drum indicates that we can judge the cutting state and accurately identify the coal-rock cutting state from the perspective of load spectrum, i.e., cutting of the roof or the floor. The quantitative evaluation of cutting performance in cases of different geological conditions and cutting conditions is of practical significance for autonomous control, optimizations of cutting trajectory and working parameters, and improvement of productivity and work safety. Cui [75] focused on the quantitative description of different geological and cutting conditions, established the complementary relationship between geological conditions/cutting conditions and cutting performance/sensor sensing parameters, and improved the accuracy and reliability of prediction and correction. He employed the coal-rock identification associated load characteristic model to describe the cutting load amplitude and direction of coal rock in cases of the drum cutting different roof and floor as well as cutting distinct dirt band and bedding joint states. Meanwhile, he monitored the differences in the vibration and noise under different coal-rock occurrence conditions. Luo [76] believed that the existing dynamic analysis of the shearer drum assumed the coal seam homogeneity, but did not consider the discontinuous characteristics of the coal seam at coal-rock interface and its interaction with the pick and drum. Especially, mechanical mutation behaviors and stress distribution states have not been investigated in cases of the discontinuous impact and friction between the pick and the coal seam. When the pick and drum are subjected to more severe impact and friction while cutting the coal seam at the coal-rock interface, it exhibits significant discontinuity. That makes it difficult to effectively control and predict the motion law and dynamic behavior of the drum, and to ensure the reliability of the shearer [77–81]. Xuan et al. [82] proposed the possibilities of increasing the efficiency of separating coal from the massif by improving the pick alignment schemes of shearer cutting drums. Given the existing structural limitations of the radial extension of the picks and the thickness of the cuts, an increase in efficiency was achieved by using combined series-group schemes for arranging picks, including energy-efficient cutting, paired and group with a larger cross-sectional area of the cuts and, therefore, with a larger particle size of the separated coal fragments, reducing dust yield and specific energy consumption.

During the coal-rock cutting, especially the cutting of semi-coal, rock and hard rock, non-uniformities of the physical and mechanical properties of coal rock induce the random vibration load of the shearer pick [83,84]. In addition, a great deal of vibration (vibrations of motor and traction transmission gearbox [85], vibration due to unevenness of mining face floor [86] and impacts (meshing impact between pin row and pin teeth of the shearer traction wheel [87], impacts due to changing meshing stiffness and manufacture error of transmission gear) is transmitted to the pick, which accelerates the random vibration of the pick. Meanwhile, the random vibration of the shearer pick is affected by structural parameters, kinematic parameters and other factors as shown in Table 4.

Table 4. Influence factors of shearer pick vibration.

Structural Parameters of Shearer [88]	**Kinematic Parameters of Shearer [89,90]**	**Other Factors [88–90]**
Pick type	Rotational speed of drum	Cutting conditions (straight cutting, oblique cutting)
Pick configuration	Traction speed	Cutting process
Geometrical parameters of drum	Matching relationship between drum speed and traction speed	Joint development of coal rock
		Coal-rock hardness

In order to quantitatively demonstrate random vibration characteristics of the pick during coal-rock cutting, it is of great significance to obtain the load spectrum of the pick. Up to now, lots of researchers have investigated the load spectrums of shear picks through theoretical analyses, field tests (Table 5) and computer simulations. During theoretical analyses of shearer pick force, Soviet scholars in the 1960s calculated the cutting resistance of the wedge pick based on rock mechanics. Nishimatsu [60] obtained the formula derivation of cutting resistance and normal force. Evans [91] derived the formula for pick cutting force. Liu [92] calculated the cutting resistance based on fractal theory. Li [77] established the mathematical model of drum cutting resistance based on single pick cutting resistance. Zhang [93] calculated the cutting resistance based on the reconstruction algorithm. Zhang [94] calculated the cutting force based on dynamics theory. Ren [95] obtained the ranges of cutting force based on the Taylor formula and Tikhonov regularization. Considering computer simulation methods of shearer pick force, there are the finite element method [96,97], discrete element method [62,98,99] and Matlab simulation method [100,101]. In the finite element method, the finite element model of coal seam cutting by shearer is established using Ansys/LS-DYNA. The forces are exerted on the drum and picks during cutting, and the load spectrums of the picks are obtained. Meanwhile, the effects of the structural parameters of the shearer cutting unit, kinematic parameters of the shearer, and shearer cutting condition on the load spectrums are investigated, respectively. In the discrete element method, EDEM software is employed to establish the discrete element model of the drum and coal rock through the settings of the mechanical parameters of particles and contact parameters between drum and coal rock, which can induce pick forces during cutting and load spectrum of the pick. In the Matlab simulation, the input is the pick structure, kinematic parameters and coal-rock characteristics, and the simulation angle and step size are determined. Afterwards, the loop variables of the rotation angle and pick number are set to calculate the pick position and pick force. When the pick number is larger than the total pick number and rotation angle larger than 360°, the pick and drum load spectrums are the output.

Table 5. Field tests of shearer pick forces.

Measurement Methods	Research Results
Cutting current of drum	Random load of cutting unit [102]
Pin shaft strains of shearer rocker Drum torque	Drum load spectrum of drum load [103,104]
Equivalent pick holder load	Pick forces at different transversal positions [105]
Strain of pick seat and torque of rocker arm idler shaft	Three-dimensional force and torque of the pick [88]
Tooth sleeve rear end force sensor. Rear end force transducer of pick sleeve	Cutting resistance of the pick [96]
Three-dimensional load cell	Normal and tangential forces of the pick [106]

Typical load spectrums of the pick during coal rock mining of thin coal seams under different working conditions are investigated [107–109]. The pick force shows the large impact as the shear drum cuts into the coal wall; the pick forces during coal-rock cutting change periodically, and pick forces along three directions exhibit different evolutions. In cases of different coal-rock types, the overall pick force during coal rock cutting decreases in the order of mudstone, hard coal and soft coal [108,109]. In coal seams with dirt bands, the pick force exhibits the largest value at the middle locations of coal seam. Meanwhile, the thickness of dirt bands greatly affects the ranges of vibration time and vibration amplitude. Zakharov et al. [110] thought that the parameters of the cutters and their spatial orientation relative to the end of the blade of the screw executive body had a significant impact on the power and energy performance of coal-mining combines. They have identified the extent to which the spatial orientation of the cutter affects the power and energy parameters of the cutting process. It was found that small values of the angle of inclination of the cutter were optimum for the cutting forces, and the lateral component of the load on the cutter decreased with increasing angle of inclination. Boiko [111] compared results of theoretical investigations into the external forces acting on the cutter drum of a shearer with results obtained using strain gauge measurements taken on the cutter picks using a reduced-scale surface test rig. He found external forces to be random in nature and to have similar properties to those of white noise, which did not contradict the results of strain gauge measurements taken underground.

4.2. Mechanical Model of the Pick Force

During the coal rock cutting, the pick force directly affects the pick safety and reliability. Previous researchers [112–115] have obtained the forces of any pick along distinct directions at the working face. Evans [91] has derived the formulas for the estimation of cutting forces based on the uniaxial compressive strength and shear properties of the rock. Rostami et al. [116] introduced a prediction model of the cutting forces of the pick. Standard cutting test procedures were developed by Roxborough and Phillips [117] to measure cutting forces of the pick when cutting various rock samples. The trends in cutting forces, breakout angles and cutting areas, have been investigated by Dogruoz and Bolukbasi [118]. As shown in previous studies [119–121], the cutting speed did not affect pick forces, and no significant relationship was observed between normal force and skew angle. Copur et al. [120] revealed that the cutting pattern significantly affected pick forces and cutting efficiency. Park et al. [122] reported that the pick cutting forces in the positive skew angle were always lower than those in the negative skew angle. Hurt [123] performed rotary cutting tests on sandstone specimens with different skew angles of a pick at a 45° attack angle, and they found that the skew angle of up to +30° had no significant effect on the cutting force. Kim et al. [121] explored the effect of the skew angle on the cutting force of the pick through a series of linear cutting tests, and they observed no general tendency in the normal and cutting forces of the pick. Choi et al. [124] conducted the full-scale linear cutting tests on mortar specimens with 0° and +6° skew angles at a 55° attack angle, and indicated that a +6° skew angle was favorable owing to less fluctuations in the cutter forces at different penetration depths. Dogruoz et al. [125] conducted full-scale laboratory cutting tests to obtain the cutting forces. In addition, they measured mechanical and physical properties of rock samples for assessment of the variation of specific energy as a function of rock properties. Li et al. [126] analyzed the stress conditions of the pick when the spiral drum was cutting coal rock with different occurrence, and revealed the reasons for wear of the pick at the outer edge of the end plate. Zhao et al. [127] believed that when the coal seam contained inclusions, the load on the drum was not only affected by the distribution, content, physical and mechanical properties of the inclusions, but also affected by the action form of the pick and the inclusion, and the number of picks cutting the inclusion at the same time. Skipochka et al. [128] analyzed the correlation between the "cutting resistance" parameter and the ultimate strength of rocks. Meanwhile, they proposed the three force components within a cutter when measuring the coal cutting resistance. Finally, the dependence of coal cutting resistance on the cutting depth was presented.

5. The Coal-Rock Cutting Mechanism

5.1. Coal-Rock Cutting Process by the Pick

During the coal-rock cutting process of the shearer pick, the pick impacts the coal rock with the speed v which causes high contact stress at a small contact area [129–131]. When the contact stress reaches the limit value, the coal rock shows the partial breakage and thus the induced compact core of coal powder. As the cutting process continues, the compact core of coal powder is discharged along the cone surface of pick body at a high speed, causing the expansions of coal breakage and compact core areas. The coal powder in the compact core accumulates the extrusion-induced energy, and the pressure continues to act on the compact core. As the compact core expands to the contact point D, the coal rock shows small pieces spalling. The coal powder in region II is spewed out at a high speed due to strong compression, and presents strong friction with the pick cone surface. The accumulation region I at the pick tip moves with the pick and shows the wedging effect on the coal rock. As the pick move to point B, the compact core, under enough compressive stress, induces shear cracks in the coal-rock. When the cracks expand to the coal surface, the region BCD of the coal rock spalls. The coal rock, as a material with high brittleness, mainly presents three cracks, i.e., the open crack, sliding crack and tearing crack. However, the open crack plays a dominate role during coal rock breakage by the pick.

It is important to evaluate the cutting performance of pick to determine a machine's capacity and operational parameters. The cutting performance of a pick depends on various parameters, such as the geometry (i.e., cutter type, cutter dimensions, cutter tip angle, and shape), cutting conditions, such as cut spacing, penetration depth, cutting angles, cutting pattern, cutting speed, and the mechanical properties of the rocks. Many studies have been conducted to establish the relationship between the cutting performance of various machines and rock properties [132–138]. Park et al. [122] conducted a series of cutting tests to explore the effect of the skew angle of a point-attack pick on the cutting performance. They found that the positive skew angle was preferred with around +10° being optimal for the selected pick cutter in terms of cutting efficiency and structural stability. Dogruoz et al. [125] investigated the cutting process of low- to medium-strength rocks. McFeat-Smith [139] studied the relationship between specific energy and rock properties, and proposed estimation formulas for specific energy based on rock properties. Fowell et al. [133,140] have set forth the standard test setting with the cutting depth of 5 mm. Meanwhile, the laboratory specific energy has been calculated by $SE = Fc/Q$ [58,133]. In the equation, SE is the laboratory specific energy, MJ/m^3, Fc is the cutting force, kN, and Q is the yield per unit length of cut, m^3/km.

When the shearer drum cuts a coal seam with dirt bands, the cutting object has changed from simple coal to a coal rock mixture. Therefore, the coal-rock interface affects the cutting performance of the shearer to a certain extent. When encountering gangue and hard inclusion coal seams, caving mining or blasting mining is usually employed. However, this mining method easily presents a low coal recovery rate and roof fall, which thereby affects the normal production [17,18]. Attributed to the large difference between the strengths of various rocks, some coalfield roofs are difficult to collapse, while others are very easy to collapse. During mining of thin and extremely thin coal seams, the shearer can easily cut the top and rub the bottom; the strength of the roof and floor strata affects the cutting performance of the shearer [141]. Tiryaki et al. [142,143] studied the relationship between the specific energy consumption of the pick and coal rock characteristics under the condition of linear cutting. They pointed out that the specific energy consumption was significantly affected by the viscosity coefficient, effective porosity, and pore volume of the coal rock materials. Meanwhile, they proposed that the Poisson's ratio, tensile strength and hardness exhibit a linear relationship with the specific energy consumption of the pick.

5.2. Pick Failure Mechanisms

Although the ability of existing shearer drums to cut hard coal has been improved, most shearer drums cannot cut rocks. Meanwhile, the ability to cut thin coal seams, small faults and coal seams with dirt bands is still insufficient. The shearer drums cannot work stably in coal seams with faults and sandstone bands [144,145]. Especially when cutting the coal seam at the coal-rock interface, the pick will suffer from excessive wear and fatigue failure due to the long-term large impact load, resulting in broken and missing teeth. That not only reduces cutting performance, but also brings harm to the normal operation of the cutter.

The cutting picks on the shearer operate in a complex and stressful environment, i.e., the rotation and advancement rate from the machine side as well as geomechanical conditions of the coal seam. They transfer the energy from the shearer to the coal body, thus causing stress concentration in the rock and ultimately leading to chip formation and coal fragmentation. Therefore, the failure of the picks results in the extraction stoppage, and thereby causes the extra operational costs and production loss [74,146–148]. In addition, failed picks may pose an increased risk to personnel and production if not replaced in time, for example, causing frictional ignition in underground coal mining production [149]. Dewangan et al. [44] thought a number of parameters, such as pick geometry, pick body material, mounting configuration, depth of cut and rock properties, influence the pick performance.

During coal rock cutting, the main failure modes of the shearer pick are pick wear, alloy head shedding, pick body bending and pick body fracture. It is found that the pick wear accounts for 45–50% of pick failure [94,150,151]. Pick wear mechanisms are abrasive wear, fatigue wear and corrosion wear [152], of which abrasive wear dominates. The generally used pick material is alloy steel (Table 6) [153–155]. In order to obtain a high wear-resistant pick material, the carburizing process is employed [80]. In fact, the pick wear degree is affected by occurrence conditions of coal rock seams, pick layout (installation angle, pick number, et al.), pick structural parameters (diameter, tip angle and cone angle) and the kinematic parameters of the shearer. Another important factor affecting the pick service life is pick body fracture, which involves the crack initiation, propagation and final rupture [152]. However, the reasons for pick fracture may be residual stress-induced pick defects during manufacturing [156], crack initiation and propagation due to instantaneous pick force exceeding the ultimate strength of the pick material [157–161], and the improper operation by the shearer operator [158]. In addition, the premature failure of the pick will be accelerated due to a mismatch between pick type and coal rock type, high dust concentration at the working face [162,163] and a wet corrosive medium [164]. Further, Eshaghian et al. [165] investigated failures of coal shearer picks in the Parvadeh coal mine in Iran, as well as the main mechanisms and causes for pick failures. The reliability of picks is critical to the productivity of the shearer [166]. Eshaghian et al., believed that pick body wear, breakage of the pick tip, slimming of pick body, and separation and removal of the pick tip, are the most frequent failures and wear modes of studied picks.

Table 6. Commonly used pick materials.

Material	Processing Technology	Hardness/HRC	Tensile Strength/MPa
40Mn2B	Quenching and tempering	35–50	980
ZG45Cr4SiMoVRE	Air quenching and high temperature tempering	50–52	1730
Si-Mn-Mo	Quenching and tempering	41–49	1600
35CrMnSi	Isothermal quenching	42–44	1600

In order to improve the cutting performance and reduce wear failure of the pick, we should pay more attention to the selection of structural parameters and layout of the pick. Parshyna and Parshyn [167] proposed the relationship between the manufacturing system stiffness, and the machining accuracy and quality, and developed a system of mathematical models. Meanwhile, large coal block spalling and energy consumption during coal rock cutting should be fully considered [88,168]. During the design of the drum, we should arrange as few picks as possible, while too few picks will induce larger pick force and intensified wear. According to the layout of the picks, the commonly used layouts of the end plate picks of the drum are Y type, -type and S type layouts [1,169]. Therefore, the number, layout and installation angle of end plate picks should be determined according to actual working conditions, in order to improve the mechanical characteristics and prolong the service lives of the picks [170]. In cases of harsh cutting conditions, we should increase the number of end plate picks [168] and mount inclined picks to avoid side wear of the end plate [171]. According to the layout of picks on the drum, the optimal pick line distance is related to the coal-rock type, shearer operation parameters and pick structural parameters [161,172]. Too large a pick line distance causes increased pick force and accelerated pick wear, while too small a pick line distance reduces the cutting efficiency of the shearer [173,174]. Kumar et al. [175] proposed that reducing the "clearance angle" reduces the surface temperature and wear, and increases pick lifetime. Liu et al. [176] explained that wear area decreases by increasing the height of the pick tip, pick tip angle and the cutting angle. Cheluszka et al. [177] found that conical picks have a much longer service life compared to radial picks, due to the possibility of spontaneous rotation in pick holders, and even wear and tear of their tip around the entire perimeter. Many coal rock cutting test rigs, as shown in Figure 3, have been developed in order to reveal the cutting performance and pick failure mechanisms [178–182].

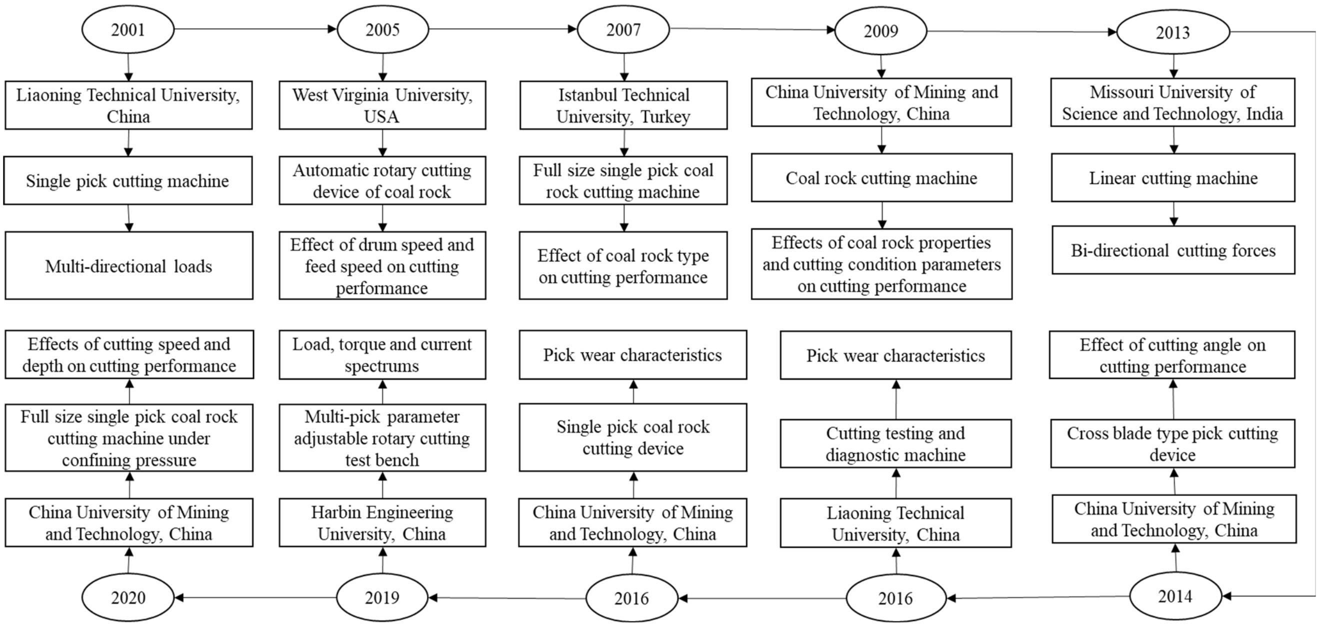

Figure 3. Development of coal rock cutting test rigs by the pick.

6. Service Safety Evaluation of the Pick Based on Wear and Fatigue

6.1. Pick Wear

The wear of the pick is important for estimating the downtime of the cutting machines [121]. The degree of pick wear greatly affects the cutting efficiency, energy consumption and service life of the shearer drum. Therefore, the quantitative evaluation of pick wear is of great theoretical significance to the determination of pick deterioration grade and prediction of pick service life. In general, pick wear is mainly measured through the weight loss method [183] and three-dimensional morphology recovery method [184,185]. Traditional three-dimensional morphology recovery technologies, i.e., the shape from shading method, stereovision method and structured light method, have limitations in obtaining accurate morphologies [185]. However, the focused morphology recovery technique has the advantages of non-occlusion, strong practicability, high accuracy and a simple algorithm, which can make up the limitations of traditional three-dimensional morphology recovery technologies. In order to obtain the three-dimensional morphology of pick cone and pick wear rate, the pick wear measurement system has been established combining the normal distribution operator filtering based on image processing method, improved focus evaluation function, focused morphology recovery method, and optimization design method. Figure 4 shows the pick wear measurement system based on the focused morphology recovery technique [16]. Kim et al. [186,187] investigated the effects of the skew angle of a pick cutter on its wear phenomenon using a frictional ignition test machine, and they reported the importance of the skew angle on the wear behavior of a pick cutter.

During coal rock cutting, several characteristics (acoustic emission signal, vibration signal, current signal, power signal, etc.) can be employed to indirectly reflect the degree of pick wear. It is proposed that the picks with distinct wear degrees exhibit different characteristics of acoustic emission signals and vibration acceleration signals during coal-rock cutting [188–190]. It is indicated that the amplitudes of vibration acceleration and the acoustic emission signal increases with increasing wear degree. Furthermore, many scholars have established wear models of shearer picks using EDEM [191,192], ABAQUS [193], ANSYS [194] and Hyperworks [195]. Correlation models between operating parameters (rotational speed, installation angle and pick tip angle) and pick wear degree are established to provide the theoretical basis for the quantitative evaluation of pick wear [196,197]. Meanwhile, the infrared temperature and current signals of picks with distinct wear degrees are measured during coal rock cutting tests in order to establish the sample database of multi-feature signals, which can realize the online detection of pick wear degree [198–200]. The training and learning of samples of multi-feature signals are conducted to establish the neural network feature signal fusion model (Figure 5) to realize the online monitoring and accurate identification of pick wear degree [201]. In addition, X-ray technology and support vector machine technology have also been employed in the detection and prediction modelling of pick wear degree [44,149,202,203]. Tan et al. [204] proposed that pick wear mechanism was the abrasive wear attributed to the small amount of hard materials such as A1203 in the coal seam containing gangue. Alber [203] studied the relationship between the rock Saichal friction coefficient and physical and mechanical properties of the rock, evaluated the rock abrasiveness and predicted the pick wear loss.

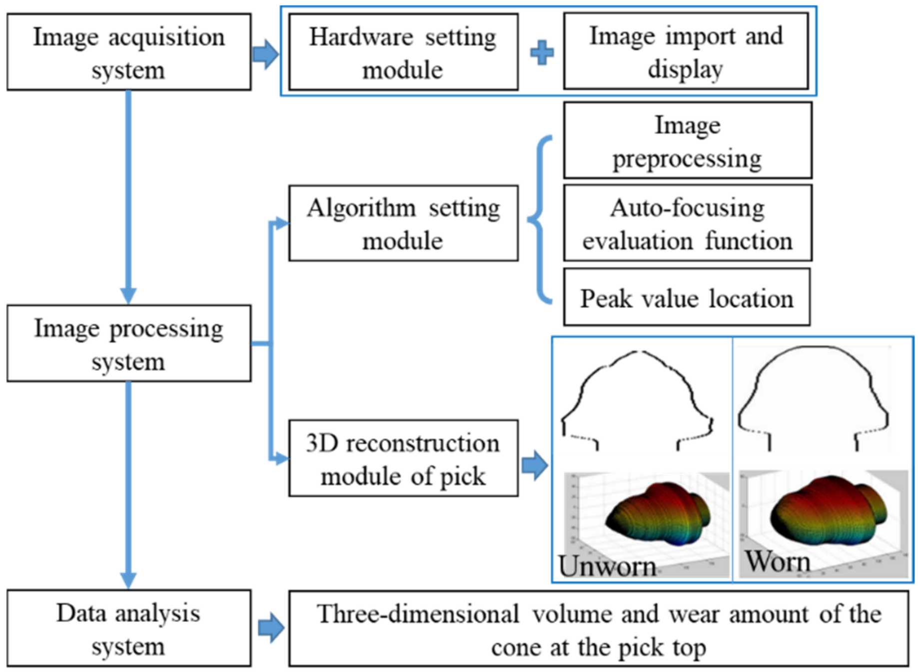

Figure 4. Pick wear measurement system.

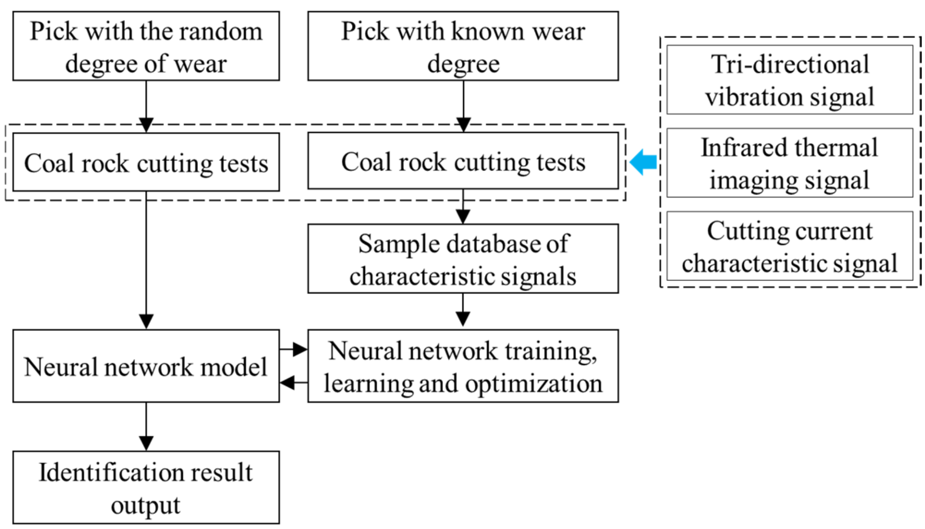

Figure 5. Neural network feature signal fusion model of pick wear degree.

6.2. Quantitative Evaluation of the Service Safety of the Pick

During coal rock cutting, the wear, fatigue and corrosion of the pick causes its gradual deterioration and thereby the dynamic change of reliability, i.e., gradual reliability (Wang et al., 2012). As the pick deteriorates to a certain extent and cannot bear the instantaneous impact or fatigue load, the pick body fractures, greatly affecting the coal rock cutting safety and reliability. Previous studies mainly focus on the reliability and reliability sensitivity of the pick, employing mathematical statistics and probability theory [205], reliability theory [206,207], artificial neural network and finite element methods. Krzysztof et al. [30] established the reliability model of a rotating pick. Meanwhile, they proposed that the evaluation method based on the average or extreme value caused the overestimation or underestimation of pick failure risk. Sun [208] studied the reliability and reliability sensitivity of picks during coal rock cutting, employing the ANSYS/LS-DYNA, neural network, and first-order second-moment theory (Figure 6a). Zhang [160] proposed the wear reliability and residual life of pick based on the gamma process and Bayesian method (Figure 6b).

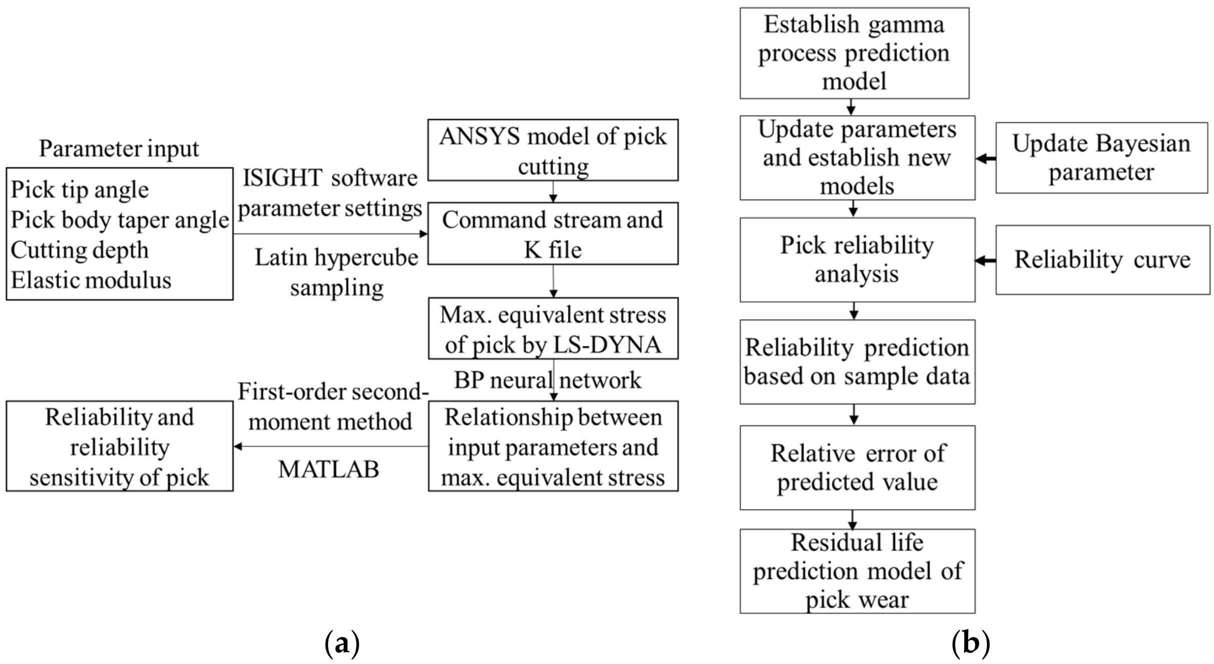

Figure 6. Prediction flow charts of the reliability and residual life of the pick: (**a**) neural network and first-order second-moment method, and (**b**) gamma process and Bayes method.

Considering the service life and safety factor of pick, Qin [195] investigated the effects of working conditions and cutting parameters on pick fatigue lives, based on the Radioss fatigue theory. Meanwhile, the fatigue life and fatigue safety factor of the pick were calculated using ABAQUS, Fe-Safe, and fatigue accumulation damage theory [209]. Lu et al. [210] analyzed the effect of the installation angle on pick fatigue life, employing LS-DYNA and Smith–Watson–Topper multi-axial fatigue life criterion. It is indicated that the reliability and service life of the pick can be effectively enhanced by adopting the rotating pick [203], improving the layout of picks on the shearer drum [211], improving structural parameters of the pick [212,213] and selecting high performance pick material [214,215].

6.3. Methods to Improve the Service Safety of the Pick

Johnson [216] synthesized new materials employing the carburizing treatment on the basis of a 30CrMnMo alloy, which improved the mechanical performance and wear resistance of the pick. This could prevent pick fracture and the pick head falling off due to severe load during operation, and it was pointed out that tooth corrosion and wear were main forms of pick failure. Chen et al. [217] employed the plasma surface spraying technology to realize the cladding of composite coating on the worn surface of the pick in order to improve the wear resistance and corrosion resistance of the pick. Zvonarev et al. [218] predicted the service lives of key parts of mining machinery by analyses of the energy capacity and energy distribution, and discovered distribution points of severe wear in the parts through the energy distribution, and improved the service lives of key parts through hardening treatment. Zhang et al. [219] improved the hardness and wear resistance of shearer pick body material 40Cr. Li et al. [126] studied the wear degree of the pick at different helix and locations in the case of the pick cutting hard rock, and found the main failure forms of pick. Meanwhile, they proposed the brazing, heat treatment, thermal spraying technology and plasma cladding strengthening technologies to treat the pick in order to improve its service life.

7. Research Prospect

The pick cutting structure is the "tooth" of the automatic shearer. In order to allow for the efficient cutting of coal seams, it should have high intelligence, high cutting capacity and high reliability. Complex geological conditions, such as fold structure, fault structure and magmatic intrusion, induce distinct occurrence conditions of coal rock seams (gangue, inclusion, or fault in the coal and rock). The adaptive cutting of the shearer reflects the ability of fully mechanized mining "three machines" equipment to automatically perceive the occurrence of coal seams and special structural parameters, and to adjust cutting parameters and processes without human intervention. The degree of adaptability also reflects the level of intelligent mining at the working face, and thereby the research on adaptive intelligent control methods is the focus of future research.

The fusion method for coal-rock interface detection should be focused on when dealing with complex geological conditions. During cutting, the boundary of the coal-rock interface is detected by hyperspectral or laser visual methods to correct the navigation path of the shearer operation. This fusion method can solve the problems of low accuracy and practicability of coal rock interface detection. Meanwhile, the coal mine geological data and the fine geophysical exploration results of seismic wave CT can be employed to establish the GIS models of the coal seam roof and floor in the working face. GIS models can effectively identify the coal-rock interface, and is the basis for realizing the automatic sensing of coal seams and adaptive cutting of shearers. However, the accuracy of geological exploration needs to be further improved. The accuracy of coal seam thickness distribution, coal seam roof and floor elevation reflected by the coal seam geographic information system in the working face is an important factor affecting the cutting path planning of the shearer. However, according to the current accuracy of seismic CT fine geophysical exploration, it is not reliable to plan the cutting path completely depending on the data of the coal seam geographic information system of the working face. Therefore, the data precision improvement technology of the coal seam geographic information system of the working face should be investigated from the perspective of detection methods, or based on the knowledge of coal seam geological experts and historical cutting conditions.

Under complex geological conditions, the effects of geological conditions such as coal rock gangue, inclusions and small faults on the coal-rock cutting mechanisms are not clear. The coal rock is heterogeneous and anisotropic due to the influence of geostress and confining pressure. The composition and performance of the coal wall in different regions are different. Comprehensive consideration of the working conditions of coal seams, including dirt bands and inclusions, can provide a more comprehensive scientific basis for the design of shearer spiral drums. The effects of actual working conditions on pick cutting loads should be fully considered, and the theoretical calculation model of the drum load spectrum should be improved, according to the different properties of coal in different regions, the most suitable shearer drum parameters, and kinematic parameters. Meanwhile, the simulation models and theoretical system of coal rock cutting considering complex geological conditions are not perfect. The prediction accuracy of load feature recognition models depends on the number of samples. In the future, targeted sample control expansion should be carried out according to the geological conditions of different working faces. In order to obtain the force information of the spiral drum in cases of different working conditions, the coupled discrete element and dynamic simulations can be employed to reflect the actual working state of the shearer.

Meanwhile, we should establish the pick selection system suitable for different complex geological conditions (for example, severe pick wear indicating the selection of a pick with high plasticity and toughness, and a drum and pick with strong breakage capacity in the case of coal rock with more gangue and faults). It is of great significance to propose the real-time automatic detection method of shearer pick wear suitable for complex geological conditions, and to investigate cutting load models for drum picks considering complex geological conditions, which can enrich the theory of coal-rock cutting using a shearer. There are many factors affecting the coupling behavior of the shearer spiral drum and coal rock, and its wear characteristics. The effects of spiral drum structure parameters and temperature field on pick wear should be fully considered in order to improve the research system of spiral drum wear characteristics in the subsequent research.

Shearer pick reliability is the quality index of a full life cycle, which covers reliability design, reliability enhancement, reliable materials, reliability operation and maintenance. It is affected by the product manufacturing quality and user operation and maintenance level. However, there is a lack of a digital, networked, intelligent operation and maintenance platform for shearer picks in cutting coal rock. Meanwhile, only through in-depth study of pick failure can we put forward corresponding countermeasures regarding aspects of design, manufacturing and use to reduce the possibility of pick failure, improve the reliability of pick use, and extend the service life of the pick. In production practice, this would not only reduce pick use and the purchase cost, but also greatly shorten the maintenance and replacement time of the pick and improve coal production efficiency. During pick use, the following countermeasures should be taken on site. We have to strengthen the daily inspection of the shearer pick, especially in the case of special geological structural zones and hard rocks. The service cycle of the pick should be registered, and the proportion of new and old picks should be reasonably distributed in order to avoid a large number of picks entering the fatigue fracture period. We have to strengthen the welding process of the alloy head and increase the welding strength and impact resistance.

In future researches, we will mainly establish qualitative and quantitative analyses on the gradual deterioration in performances of shearer picks during coal rock cutting under complex geological conditions, propose a dynamic monitoring system of stresses and strains in shearer picks, put forward the selection scheme of shearer picks under complex geological conditions, and obtain the optimal design scheme of arrangement of shearer picks against friction fatigue failure.

8. Conclusions

The correlations between complex geological conditions and wear deterioration, as well as the safety and reliability evaluation of shearer picks have been revealed in the present study. Meanwhile, the influencing factors of wear deterioration of shearer picks have been analyzed. In order to evaluate coal rock cutting performances of shearer picks under complex geological conditions, geological occurrence conditions of coal rock seams are classified according to coal seam thickness and coal lithotype. The mechanical coal rock breakage by shearer picks is presented through theory, finite and discrete element analyses, and experiment. During coal rock cutting, the load spectrums of the pick and the mechanical model of the pick force are discussed. According to the coal rock cutting mechanism, the coal rock cutting process by the pick, pick failure mechanisms and the development of coal rock cutting test rigs by the pick are presented. In order to evaluate the service safety of the pick based on wear and fatigue, the pick wear, quantitative evaluation of service safety of the pick, and methods to improve the service safety of the pick are introduced. Finally, the research prospect is proposed to outline the implications for the development trend of coal rock cutting with shearer picks under complex geological conditions. The present study is of great significance to understand failure modes and cutting mechanisms of shearer picks, quantitatively evaluate pick safety, promote the automatic and intelligent cutting of coal rock seams, and thereby to improve the production efficiency of shearers.

Author Contributions: Conceptualization, methodology, formal analysis, data curation, writing—original draft preparation, writing—review and editing, project administration, funding acquisition, L.W.; formal analysis, data curation, D.W. and C.F.; supervision, D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Fundamental Research Funds for the Central Universities, grant number 2019QNA13.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would also like to thank contributions of Bo Wang, Hailang Chong, Wei Xu, Yuewei Sun, Xuefeng Wei, Ziao Xue, Yuan Sun, Liang Tang.

Conflicts of Interest: The authors declare no conflict of interest. We identify and declare there are no personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Ge, S.R. The development history of coal shearer technology (Part seven) -cutting device. *China Coal* **2020**, *46*, 15–29.
2. Kazanin, O.; Sidorenko, A.; Drebenstedt, C. Intensive underground mining technologies: Challenges and prospects for the coal mines in Russia. *Acta Montan. Slovaca* **2021**, *26*, 60–69.
3. Peng, H.Y. *Study on the Movement and Reverse Failure Characteristics of Overburden Strata when Coal Face Cross Over Fault*; Chongqing University: Chongqing, China, 2020.
4. Liu, C.S.; Liu, Y.T.; Liu, R.H.; Bai, Y.F.; Li, D.G.; Shen, J.X. Correlation load characteristic model between shearer cutting state and coal-rock recognition. *J. China Coal Soc.* **2022**, *47*, 527–540.
5. Zhu, M.B. *Dynamic Construction of High-Precision 3D Geological Model for Coal Mining Panel*; China Coal Research Institute: Beijing, China, 2021.
6. Liu, C.S.; Yu, N.J.; Zhang, Y.J. Loading process and performance evaluation of shearer drum for extremely thin coal seams. *J. Heilongjiang Univ. Sci. Technol.* **2020**, *30*, 86–93.
7. Hao, Z.Y.; Zhang, P.; Song, Z.D. Cut pick cut line distribution and the findings of a study of load spectrum. *J. Mech. Strength* **2017**, *39*, 7.
8. Chen, Y.X.; Wang, F.; Li, H.T.; Zhou, X. Structural development characteristics of Xiaozhuang Coal Mine in Binchang mining area and their impact on mining. *China Coal* **2019**, *45*, 111–115.
9. Liu, J.X.; Xian, X.; Zhang, C. Research on the influence of various cutting speeds of conical pick on coal cutting process. *J. Shangdong Univ. Sci. Technol.* **2022**, *41*, 66–74.
10. Miao, S.G. *Study on Coal-Rock Characteristics Identification Method Based on GPR and ESR.*; China University of Mining and Technology: Xuzhou, China, 2019.
11. Li, C.L.; Liu, C.A.; Ma, B. Key technology of fully mechanized mining in thin seam with hard gangue. *Coal* **2018**, *27*, 20–22. [CrossRef]
12. Krivosheev, Y.T.; Koval, T.P. Utilisation of acoustic signals from shearer picks to indicate inclusions in seams. *Ukraine* **1977**, *21*, 32–33.
13. Ordin, A.A.; Okol'nishnikov, V.V.; Rudometov, S.V.; Metel'kov, A.A. Evaluation of drum shearer capacity in coal seam with variable geomechanical and geotechnical characteristics. *J. Min. Sci.* **2019**, *55*, 57–65. [CrossRef]
14. Yan, C.Z.; Zhang, W.Z.; Guo, S.Q.; Su, X.B. Occurrence features of deep coal seam and characteristics of coal petrography in Jiaozuo mining area. *Clean Coal Technol.* **2012**, *18*, 43–45.
15. Zheng, C.; Ma, D.M.; Xia, Y.C.; Chen, Y.; Li, W.B. Development mode and tectonic control of CBM enrichment. *Hancheng Min. Area Coal Eng.* **2021**, *53*, 89–94.
16. Zhang, Y.L. *The Discipline and General Evaluation of Main Coal Seams Occurrence in Huagou West Mine in Huaibei*; Anhui University of Science and Technology: Huaibei, China, 2009.

17. Fang, J.; Li, P. Study on occurrence and mining conditions of coal seam in Erlintu well Field. *Shaanxi Coal* **2011**, *30*, 64–66.
18. Shen, Z.M.; Yang, M. Analysis of coal seam occurrence characteristics in the third phase planning area of Yushen mining area. *Shaanxi Coal* **2020**, *39*, 92–96.
19. Fan, G.Q. Field geology and coal occurrence law in the east of Shengli Coalfield. *Pioneering Sci. Technol.* **2011**, *24*, 162–163.
20. Stopes, M.C. On the four visible ingredients in banded bituminous coal; studies in the composition of coal, No.1. *Proc. R. Soc. Lond. Ser. B Contain. Pap. A Biol. Character* **1919**, *90*, 470–487.
21. Diessel, C.F.K. An appraisal of coal facies based on macerals characteristics. *Aust. Coal Geol.* **1982**, *4*, 474–483.
22. Renton, J.J.; Hamilton, W.M. Petrographic zonation within the Waynesburg coal. *Int. J. Coal Geol.* **1988**, *10*, 261–274. [CrossRef]
23. Wang, S.C.; Xu, X.C. Lithotypicals seperation and their combustion kinetics. *J. Eng. Thermoph.* **1996**, *17*, 229–233.
24. Zhao, S.H.; Yu, T.T.; He, Y.C.; Ji, S.Y.; Hu, Y.J.; Chen, Y. Classification of macroscopic type based on logging in Shizhuang area. *China Min. Mag.* **2017**, *26*, 382–384.
25. Cui, C. *Logging Identification and Quantitative Evaluation of Coal Macrolithotypes: A Case of Zhengzhuang Field*; China University of Geosciences: Beijing, China, 2021.
26. Jia, J.G. *Research on Rock Breaking by Mechanical Shock and High Pressure Foam Fracturing*; China University of Mining and Technology: Xuzhou, China, 2021.
27. Liu, S.; Ji, H.; Liu, X.; Jiang, H. Experimental research on wear of conical pick interacting with coal-rock. *Eng. Fail Anal.* **2017**, *74*, 172–187. [CrossRef]
28. Wang, S.; Li, X.; Yao, J.; Gong, F.; Li, X.; Du, K.; Tao, M.; Huang, L.; Du, S. Experimental investigation of rock breakage by a conical pick and its application to non-explosive mechanized mining in deep hard rock. *Int. J. Rock. Mech. Min. Sci.* **2019**, *122*, 104063. [CrossRef]
29. Bołoz, Ł. Results of a study on the quality of conical picks for public procurement purposes. *New Trends Prod. Eng.* **2018**, *1*, 687–693. [CrossRef]
30. Krauze, K.; Bołoz, Ł.; Wydro, T. Parametric factors for the tangential-rotary picks quality assessment. *Arch. Min. Sci.* **2015**, *60*, 265–281.
31. Krauze, K.; Mucha, K.; Wydro, T. Evaluation of the quality of conical picks and the possibility of predicting the costs of their use. *Multidiscip. Asp. Prod. Eng. MAPE* **2020**, *3*, 491–504. [CrossRef]
32. Li, X.F. *Theoretical and Experimental Study on Rock Cutting in Deep Mining*; China University of Mining and Technology: Xuzhou, China, 2018.
33. Li, N. *The Measurement Method and System of Mining Pick Wear Based on Shape from Focus*; Taiyuan University of Technology: Taiyuan, China, 2019.
34. Yasar, S. A General Semi-Theoretical Model for Conical Picks. *Rock Mech. Rock. Eng.* **2020**, *53*, 2557–2579. [CrossRef]
35. Mucha, K. The new method for assessing rock abrasivity in terms of wear of conical picks. *New Trends Prod. Eng.* **2019**, *2*, 186–194. [CrossRef]
36. Sikora, W. *Determination of Forces and Energy Consumption of Excavation with Conical Picks*; The Silesian University of Technology Press: Gliwice, Poland, 2000.
37. Yasar, S. Predictive plots for conical pick performance using mechanical and elastoplastic properties of rocks. *J. Rock Mech. Geotech. Eng.* **2020**, *12*, 1027–1035. [CrossRef]
38. Krauze, K.; Skowronek, T.; Mucha, K. Influence of the hard-Faced layer welded on tangential-Rotary pick operational part on to its wear rate. *Arch. Min. Sci.* **2016**, *61*, 779–792. [CrossRef]
39. Krauze, K.; Bołoz, Ł.; Wydro, T.; Mucha, K. Durability testing of tangential—Rotary picks made of different materials. *Min. Inform. Autom. Electr. Eng.* **2017**, *1*, 26–34. [CrossRef]
40. Bołoz, Ł. Directions for increasing conical picks' durability. *New Trends Prod. Eng.* **2019**, *2*, 277–286. [CrossRef]
41. Scieszka, S.; Filipowicz, K. *Materiały na Narzedzia Górnicze*; Wydawnictwo Politechniki Slaskiej: Gliwice, Poland, 2001. (In Polish)
42. Garbiec, D.; Siwak, P. Microstructural evolution and development of mechanical properties of spark plasma sintered WC–Co cemented carbides for machine parts and engineering tools. *Arch. Civ. Mech. Eng.* **2019**, *19*, 215–223. [CrossRef]
43. Nahak, S.; Dewangan, S.; Chattopadhyaya, S.; Krolczyk, G. Discussion on importance of tungsten carbide–cobalt (WC-Co) cemented carbide and its critical characterization for wear mechanisms based on mining applications. *Arch. Min. Sci.* **2018**, *63*, 229–246.
44. Dewangan, S.; Chattopadhyaya, S. Characterization of wear mechanisms in distorted conical picks after coal cutting. *Rock Mech. Rock Eng.* **2016**, *49*, 225–242. [CrossRef]
45. Bołoz, Ł.; Kalukieiwcz, A.; Galecki, G.; Romanyshyn, L.; Romanyshyn, T.; Giménez, R.B. Conical Pick Production Process. *New Trends Prod. Eng.* **2020**, *3*, 231–240. [CrossRef]
46. Bakhtavar, E. Determination of optimum drum shearer for tabas mine using decision making process. In Proceedings of the 24th International Mining Congress and Exhibition of Turkey-IMCET'15, Antalya, Turkey, 14–17 April 2015; pp. 919–924.
47. Ivanov, V.S.; Ivanova, G.M. Dependence of seismoacoustic activity of a coal seam at the face on mining intensity. *Ukraine* **1980**, *10*, 33–34.
48. Hu, D.L.; Wu, W.G.; Jin, H.S. Similarity simulation study on cutting and crushing theory of shearer. *J. China Coal Soc.* **1992**, *56*, 1–8.
49. Lindqvist, P.A.; Lai, H.H.; Alm, O. Indentation fracture development in rock continuously observed with a scanning microscope. *Int. J. Rock Mech. Min. Sci. Geomech.* **1984**, *21*, 165–182. [CrossRef]

50. Loui, J.P.; Karanam, U.M.R. Numerical studies on chip formation in drag-pick cutting of rocks. *Geotech. Geol. Eng.* **2012**, *30*, 145–161. [CrossRef]
51. Evans, I. A theory of the basic mechanics of coal ploughing. *Min. Res.* **1962**, *2*, 761–798.
52. Gao, K.D.; Du, C.L.; Jiang, H.X.; Liu, S.Y. A theoretical model for predicting the Peak Cutting Force of conical picks. *Frat. Integrità Strutturale.* **2014**, *8*, 43–52.
53. Wang, X.Z. *Experimental Study on Mechanical Behavior of Pick-Rock Cutting Process*; China University of Mining and Technology: Xuzhou, China, 2016.
54. Wang, L.P.; Jiang, B.S.; Zhang, Q. Calculation of peak cutting force of conical picks under conditions of dissymmetrical slotting. *J. China Coal Soc.* **2016**, *41*, 2876–2882.
55. Rojek, J.; Oñate, E.; Labra, C.; Kargl, H. Discrete elemen simulation of rock cutting. *Int. J. Rock Mech. Min.* **2011**, *48*, 996–1010. [CrossRef]
56. Su, O.; Akcin, N.A. Numerical simulation of rock cutting using the discrete element method. *Int. J. Rock Mech. Min.* **2011**, *48*, 434–442. [CrossRef]
57. Ma, C. *Research and Discrete Element Simulation on Rotary Coal Cutting Process of Conical Pick*; Shandong University of Science and Technology: Qingdao, China, 2018.
58. Balci, C.; Demircin, M.A.; Copur, H. Estimation of optimum specific energy based on rock properties for assessment of roadheader performance. *J. Afr. Inst. Min. Metall.* **2004**, *104*, 633–642.
59. Bakar, M.Z.A.; Gertsch, L.S. Saturation effects on disc cutting of sandstone. In *Proceedings of the 45th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, USA, 26–29 June 2011*; Kulatilake, P., Wang, L.Q., Tang, H.M., Eds.; American Rock Mechanics Association: Alexandria, VA, USA, 2011.
60. Nishimatsu, Y. The mechanics of rock cutting. *Int. J. Rock Mech. Min.* **1972**, *9*, 261–270. [CrossRef]
61. Xue, J.; Xia, Y.; Ji, Z. Soft rock cutting mechanics model of TBM cutter and experimental research. In *Intelligent Robotics and Applications*; Su, C.Y., Rakheja, S., Liu, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2009; pp. 383–391.
62. Menezes, P.L.; Lovell, M.R.; Avdeev, I.V. Studies on the formation of discontinuous chips during rock cutting using an explicit finite element model. *Int. J. Adv. Manuf. Technol.* **2014**, *70*, 635–648. [CrossRef]
63. Raghavan, V.; Murthy, C.; Sastry, V.R. Analysis of stresses produced and dust generation during rock cutting by ANSYS software. *Int. J. Sci.* **2014**, *3*, 595–606.
64. Guan, L.K.; Yang, T.; Ren, X.P. Influence of shearer drum crown wheel cutting pick angle to cutting loading characteristic. *Coal Min. Technol.* **2018**, *23*, 15–17.
65. Ji, F.L. *Transverse Roadheader Cutting Head Simulation and Optimized Design*; Anhui University of Science and Technology: Huainan, China, 2006.
66. Cao, X.T. *DEM Simulation Study for Picks Cutting Coal of Roadheader*; Shenyang Li Gong University: Shenyang, China, 2012.
67. Zhang, X.L. *Force Analysis of the Shearer Drum and Optimizaton of Parameters*; Taiyuan University of Technology: Taiyuan, China, 2015.
68. Mendoza, J.A.; Gamwo, I.K.; Zhang, W.A. Discrete Element Modeling of Rock Cutting Using Crushable Particles. In Proceedings of the 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, Salt Lake, UT, USA, 27–30 June 2010.
69. Van Wyk, G.; Els, D.N.J.; Akdogan, G.; Bradshaw, S.M.; Sacks, N. Discrete element simulation of tribological interactions in rock cutting. *Int. J. Rock Mech. Min.* **2014**, *65*, 8–19. [CrossRef]
70. Liu, S.Y. *Research on Cutting Performance of Shearer Drum and Cutting System Dynamics*; China University of Mining and Technology: Xuzhou, China, 2009.
71. Bakar, M.A. *Saturation Effects on Mechanical Excavatability of Roubidoux Sandstone Under Selected Rock Cutting Tools*; Missouri University of Science and Technology: Rolla, MO, USA, 2012.
72. Balci, C.; Tumac, D. Investigation into the effects of different rocks on rock cuttability by a V-type disc cutter. *Tunn. Undergr. Space Technol.* **2012**, *30*, 183–193. [CrossRef]
73. Balci, C.; Bilgin, N. Correlative study of linear small and full-scale rock cutting tests to select mechanized excavation machines. *Int. J. Rock Mech. Min.* **2007**, *44*, 468–476. [CrossRef]
74. Bilgin, N.; Demircin, M.A.; Copur, H.; Balci, C.; Tuncdemir, H.; Akcin, N. Dominant rock properties affecting the performance of conical picks and the comparison of some experimental and theoretical results. *Int. J. Rock Mech. Min.* **2006**, *43*, 139–156. [CrossRef]
75. Cui, X.D. *Study on the Abrasion of the Spiral Drum of the Shearer Under the Condition of Coal and Rock Containing Gangue*; Liaoning Technical University: Fuxin, China, 2020.
76. Luo, C.X. *Study on Cutting Characteristics of Shearer Mining Coal Seam with Coal-Rock Interface*; China University of Mining and Technology: Xuzhou, China, 2015.
77. Li, D.G. *Mechanical Model of Pick Cutter and Chaotic and Fractal Characteristics of Load Spectrum*; Heilongjiang University of Science and Technology: Harbin, China, 2011.
78. Li, G.R.; Li, M.; Tang, Q.; Lan, C. Research of fully mechanized mining technology of ultra-thin coal seam and its application. *J. Mine. Autom* **2011**, *37*, 89–92.

79. Li, H.W.; Shi, H.Y. Analysis and practice of mechanized mining technology in manless working face of thin coal seam. *J. Saf. Sci. Technol.* **2010**, *6*, 61–65.
80. Luo, Y.; Zhang, D.K.; Wang, Q.L.; Liu, H.T.; Cheng, G.; Ge, S.R. Preparation and properties of a new cutting pick of coal shearers. *Min. Sci. Technol.* **2010**, *20*, 794–796. [CrossRef]
81. Zhou, X.B.; He, X. Application of auger mining technology in extremely thin seam mining. *Coal Eng.* **2010**, *16*, 48–50.
82. Xuan, N.V.; Linh, N.; Gabov, V.V.; Lykov, Y.W. Relocation schemes of picks with cutting, coupling and group cuts on shearer cutting drums. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *378*, 012022. [CrossRef]
83. Zhao, L.J.; Tian, Z. Study of the Stability of Shearer Cutting Unit. *J. Mech. Transm.* **2012**, *36*, 14–16+34.
84. Xie, M.; Yan, J.L.; Mao, J.; Miao, L.Y.; Dong, X.R. Analysis of vibration characteristics of shearer cutting unit. *J. Mech. Strength* **2017**, *39*, 254–260.
85. Zhang, J.W.; Tan, D.J.; Jiang, Y.U.; Zhang, Z.M. Vibration characteristic analysis of electro-haulage shearer. *Colliery Mech. Electr. Technol.* **2006**, *4*, 35–37.
86. Li, X.H.; Yao, J.Q. Mathematic model of relation of shearer parameters to noise on coalface. *J. Heilongjiang Inst. Sci. Technol.* **2006**, *16*, 282–284.
87. Song, P. *Research on Vibration Characteristics and Transmission System Structure Optimization of High-Power Shearer Cutting Unit*; Liaoning Technical University: Fuxin, China, 2014.
88. Li, J.Y. *Study on Cutting Load Spectrum of Shearer*; China University of Mining & Technology: Xuzhou, China, 2017.
89. Zhang, H.Z. Optimization of cutting line spacing of drum of shearer. *Mech. Electr. Eng. Technol.* **2019**, *48*, 154.
90. Zhang, J.Y. *Research on Structure and Properties of Metal Mold Cast-In Shearer CUTTING Pick*; Dalian University of Technology: Dalian, China, 2019.
91. Evans, I. A theory of the cutting force for point-attack picks. *Int. J. Rock Mech. Min.* **1984**, *2*, 67–71. [CrossRef]
92. Liu, C.S. Fractal characteristic study of shearer cutter cutting resistance curves. *J. China Coal Soc.* **2004**, *29*, 115–118.
93. Zhang, D. *Multi-Tooth Composite Cutting Drum Reconstruction Algorithm of Random Loads Raction Characteristics*; Harbin Engineering University: Harbin, China, 2016.
94. Zhang, P. *Coal Winning Machine Cutting Load and Energy Consumption Characteristics Research*; Liaoning Technical University: Fuxin, China, 2017.
95. Ren, C.P.; Liu, R.H.; Xu, P. Interval identification model and calculation method of coal and rock load with conical pick. *J. Heilongjiang Univ. Sci. Technol.* **2020**, *30*, 5.
96. Goktan, R.M.; Gunes, N. A semi-empirical approach to cutting force prediction for point-attack picks. *J. South Afr. Inst. Min. Metall.* **2005**, *105*, 257–264.
97. Wang, L.J. Analysis of pick failure in shearer and tunneling machine and improvement measure. *Jiangxi Coal Sci. Technol.* **2017**, *2*, 118–119.
98. Piao, J.A. *Analysis of Load Spectrum on Coal Auger Bits*; Liaoning Technical University: Fuxin, China, 2010.
99. Bai, Y.F. *Load Characteristics and Coal Loading Efficiency of Slanting Drum Cutting Coal Rock*; Heilongjiang University of Science and Technology: Harbin, China, 2021.
100. Hao, Z.Y.; Mao, J. The simulation experiments research of plow bit cutting coal rock basing on Ls-Dyna. *Adv. Mater Res.* **2011**, *228–229*, 1035–1038. [CrossRef]
101. Yang, X.; Wang, Z.G.; Zhang, L.; Fu, J.X. Study on cutting tooth strength of spiral drilling shearer based on LS-DYNA. *Adv. Mater. Res.* **2013**, *805–806*, 1703–1707. [CrossRef]
102. Yang, R.F.; Li, L.; Li, X. Analysis of Load and Research on Bearing Life of Shearer Cutting Part. *Coal Mine Mach.* **2012**, *42*, 26–28.
103. Hao, Z.Y.; Zhou, Z.Q.; Yuan, Z.; Lei, Y.L.; Zhang, P. Study on fractal distribution law of cutting load of shearer based on experimental tests. *Chin. J. Appl. Mech.* **2019**, *36*, 417–423+512.
104. Li, J.M.; Wang, L.B.; Peng, M. Load Testing and Data Processing for Shearer. *Colliery Mech. Electr. Technol.* **2002**, *1*, 3.
105. Hao, S.Q. *Research on Navigation and Self-Adaptive Cutting Control Technology of Shearer Based on Coal Seam Structure*; China University of Mining and Technology: Xuzhou, China, 2017.
106. Wang, X.; Su, O.; Wang, Q.F.; Liang, Y.-P. Effect of cutting depth and line spacing on the cuttability behavior of sandstones by conical picks. *Arab. J. Geosci.* **2017**, *10*, 525. [CrossRef]
107. Liu, S.F. *Study on Cutting Principle and Mining Technology of Low-Energy-Consumption in Deep Coal*; China University of Mining and Technology: Xuzhou, China, 2020.
108. He, J.Q.; Wang, Z.W. Numerical simulation of coal breaking process of screw drum of thin coal seam shearer. *Coal Eng.* **2013**, *45*, 97–99.
109. Ma, Q. Influence of different coal seam parameters on the structural performance of coal mining machine cut-off teeth. *Mech. Manag. Dev.* **2022**, *37*, 87–89.
110. Zakharov, V.N.; Linnik, V.Y.; Linnik, Y.N.; Averin, E.A. Loading of coal mining machine tools after change in spatial orientation of picks. *Eurasian Min.* **2019**, *1*, 40–42. [CrossRef]
111. Boiko, N.G. Nature and properties of external forces acting on the cutter unit of a shearer loader. *Izv. Vyss. Uchebn. Zaved. Gorn. Zh.* **1986**, *3*, 75–79.
112. Liu, C.S.; Li, D.G. Experimental research and theoretical model on lateral force of conical pick under different cutting conditions. *J. China Coal Soc.* **2016**, *41*, 2359–2366.

113. Liu, X.H. *Research on Mechanical and Wear Characteristic of Conical Pick Interacted with Coal-Rock*; China University of Mining & Technology: Xuzhou, China, 2016.
114. Liu, S.; Chen, J.; Liu, X. Rock Breaking by conical pick assisted with high pressure water jet. *Adv. Mech. Eng.* **2014**, *6*, 868041.
115. Liu, S.; Liu, Z.; Cui, X. Rock breaking of conical cutter with assistance of front and rear water jet. *Tunn. Undergr. Space Technol.* **2014**, *42*, 78–86. [CrossRef]
116. Rostami, J.; Ozdemir, L.; Neil, D.M. Application of heavy duty roadheaders for underground development of the Yucca Mountain exploratory study facility. In Proceedings of the International High Level Nuclear Waste Management Conference, Las Vegas, NV, USA, 22–26 May 1994; pp. 17–20.
117. Roxborough, F.F.; Phillips, H.R. Experimental studies on the excavation of rocks using picks. Advances in rock mechanics. In Proceedings of the 3rd ISRM Congress, Denver, CO, USA, 1–7 November 1974.
118. Dogruoz, C.; Bolukbasi, N. Effect of cutting tool blunting on the performances of various mechanical excavators used in low-and medium-strength rocks. *Bull. Eng. Geol. Environ.* **2014**, *73*, 781–789. [CrossRef]
119. Sanio, H.P. Prediction of the performance of disc cutters in anisotropic rock. *Int. J. Rock Mech. Min. Sci.* **1985**, *22*, 153–161. [CrossRef]
120. Copur, H.; Bilgin, N.; Balci, C.; Tumac, D.; Avunduk, E. Effects of different cutting patterns and experimental conditions on the performance of a conical drag tool. *Rock Mech. Rock Eng.* **2017**, *50*, 1585–1609. [CrossRef]
121. Kim, E.; Rostami, J.; Swope, C. Full scale linear cutting experiment to examine conical bit rotation. *J. Min. Sci.* **2012**, *48*, 882–895. [CrossRef]
122. Park, J.Y.; Kang, H.; Lee, J.W.; Kim, J.H.; Oh, J.Y.; Cho, J.W.; Rostami, J.; Kim, H.D. A study on rock cutting efficiency and structural stability of a point attack pick cutter by lab-scale linear cutting machine testing and finite element analysis. *Int. J. Rock Mech. Min. Sci.* **2018**, *103*, 215–229. [CrossRef]
123. Hurt, K.G. Rock cutting experiments with point attack tools. *Colliery Guard.* **1980**, *228*, 1–5.
124. Choi, S.W.; Chang, S.H.; Lee, G.P.; Park, Y.T. Performance estimation of conical picks with slim design by the linear cutting test (II): Depending on skew angle variation. *J. Korean Tunn. Undergr. Space Assoc.* **2014**, *16*, 585–597. [CrossRef]
125. Dogruoz, C.; Bolukbasi, N.; Rostami, J.; Acar, C. An experimental study of cutting performances of worn picks. *Rock Mech. Rock Eng.* **2016**, *49*, 213–224. [CrossRef]
126. Li, Y. *The Study of Cutting Hard Rock with High Stress by the Cutting Picks*; Central South University: Changsha, China, 2012.
127. Zhao, L.J.; Tian, Z.; Liu, X.N.; Xie, B. Simulation analysis of load characteristic of thin seam shearer drum. *J. Syst. Simul.* **2015**, *27*, 3102–3108.
128. Skipochka, S.; Krukovskyi, O.; Palamarchuk, T.; Prokhorets, L. On the methodology for considering scale effect of rock strength. *Min. Miner. Depos.* **2020**, *14*, 24–30. [CrossRef]
129. Zhu, S.G. *Study on Coal and Rock Character Recognition Method in Fully Mechanized Caving Faces*; China University of Mining & Technology: Beijing, China, 2014.
130. Li, Y.; Li, X.B. Study on wear performance of pick cutting. *Min. Res. Dev.* **2012**, *2*, 85–88.
131. Hu, J.P. New developments in hardrock continuous mining abroad. *Ind. Miner. Process.* **1992**, *5*, 9–12.
132. Fowell, R.J. *Studies on the Application of Percussively Activated Tools to Reef Slotting in Some South African Quartzites*; University of Newcastle upon Tyne: Newcastle, UK, 1973.
133. McFeat-Smith, I.; Fowell, R.J. Correlation of rock properties and the cutting performance of tunnelling machines. In *Conference on Rock Engineering*; British Geotechnical Society: London, UK, 1977; pp. 581–602.
134. Gehring, K.H. A cutting comparison. *Tunn. Tunn.* **1989**, *21*, 27–30.
135. Neil, D.M.; Rostami, J.; Ozdemir, L.; Gertsch, R. Production estimating techniques for underground mining using roadheaders. *Soc. Min. Eng. Aime* **1994**, *1*, 1–11.
136. Bilgin, N.; Yazici, S.; Eskikaya, S. A model to predict the performance of roadheaders and impact hammers in tunnel drivages. In Proceedings of the EUROCK'96, Torino, Italy, 2–5 September 1996; pp. 710–721.
137. Copur, H.; Ozdemir, L.; Rostami, J. Roadheader applications in mining and tunneling industries. *Min. Eng.* **1998**, *50*, 38–42.
138. Thuro, K.; Plinninger, R.J. Roadheader excavation performance—Geological and geotechnical influences. In Proceedings of the 9th ISRM Congress, Paris, France, 25 August 1999.
139. McFeat-Smith, I. *Correlation of Rock Properties and Tunnel Machine Performance in Selected Sedimentary Rocks*; University of Newcastle upon Tyne: Newcastle, UK, 1975.
140. Fowell, R.J.; Johnson, S.T. Rock classification and assessment for rapid excavation. In *Developments in Geotechnical Engineering*; Elsevier: Amsterdam, The Netherlands, 1981; Volume 32, pp. 241–244.
141. Wang, X.; Zhao, D.; Ding, E.J. Coal-rock identification method based on terahertz spectroscopy technology. *J. Min. Strata Control* **2018**, *23*, 13–17+91.
142. Tiryaki, B.; Boland, J.N.; Li, X.S. Empirical models to predict mean cutting forces on point-attack pick cutters. *Int. J. Rock Mech. Min.* **2010**, *47*, 858–864. [CrossRef]
143. Tiryaki, B.; Dikmen, A.C. Effects of rock properties on specific cutting energy in linear cutting of sandstones by picks. *Rock Mech. Rock Eng.* **2006**, *39*, 89–120. [CrossRef]
144. Ren, D.Y. Thin Coal Seam Mining and Application of Plough in Xinqiang Coal Mine. *Shandong Coal Sci. Technol.* **2011**, *2*, 26–27.

145. Ren, F.; Liu, Z.Y.; Yang, Z.J. Weighted algorithm of multi-sensor data conflict in coal-rock interface recognition. *Appl. Mech. Mater.* **2011**, *1287*, 1908–1913. [CrossRef]
146. Hoseinie, S.H.; Ahmadi, A.; Ghodrati, B.; Kumar, U. Reliability-centered maintenance for spray jets of coal shearer machine. *Int. J. Reliab. Qual. Saf. Eng.* **2013**, *20*, 1340006. [CrossRef]
147. Sun, Y.; Li, X.S. Ineffective rock breaking and its impacts on pick failures ISARC. In *Proceedings of the International Symposium on Automation and Robotics in Construction, Sydney, Australia, 9–11 July 2014*; IAARC Publications: Pittsburgh, PA, USA, 2014; Volume 31, p. 1.
148. Shao, W. *A Study of Rock Cutting with Point Attack Picks*; The University of Queensland: Brisbane, Australia, 2016.
149. Dewangan, S.; Chattopadhyaya, S.; Hloch, S. Wear assessment of conical pick used in coal cutting operation. *Rock Mech. Rock Eng.* **2015**, *48*, 2029–2039. [CrossRef]
150. Zhang, C.H.; Zhang, N.; Wang, Y. Heat treatment technology and property study on 40cr of shearer picks body. *Adv. Mater. Res.* **2013**, *791–793*, 782–785. [CrossRef]
151. Zhang, N.; Wang, S.C.; Shi, N. The Abrasive Resistance Study about the Cutting Picker 40Cr of Coal Cutter. In Proceedings of the International Conference on Applied Mechanics, Materials and Mechanical Engineering, Wuhan, China, 24–25 August 2013; pp. 222–225.
152. Jia, L. Analysis and prevention of pick stem failure crack of shearer. *Coal Mine Mach.* **2004**, *3*, 59–60.
153. Wang, K.H. Research on strengthening technology of shearer spiral drum pick. *China Coal* **2021**, *47*, 85–88.
154. Wang, S.D. Study on the failure mechanism of shearer's pick and its improvement measures. *Min. Eq.* **2021**, 218–219. [CrossRef]
155. Wang, S.Q. *Recognition and Prediction of Catting Pick Abrasion Condition Status Based on Grey-Markov*; Liaoning Technical University: Fuxin, China, 2019.
156. Yang, Y. Analysis of the common failure modes and countermeasures of the cutting-teeth of the shearer. *Mech. Manag. Dev.* **2019**, *34*, 246–247.
157. Wang, J.H. Study on shearer pick about failure mechanism and improvement measures. *Coal Chem. Ind.* **2018**, *41*, 79–81.
158. Niu, K. Study on failure mechanism and improvement technology of shearer cutters. *Technol. Inf.* **2019**, *111*, 115.
159. Cheng, J.Q. Material selection and manufacturing technology of shearer cutting gear. *Rock Drill. Mach Pneum. Tools* **2013**, *4*, 25–30.
160. Zhang, J.Y. *Study on the Wear Status Degraded of Pick Based on Principal Component Analysis*; Liaoning Technical University: Fuxin, China, 2019.
161. Zhang, R.; Zhang, Y.; Zhu, L. Tests for dynamic characteristics of shearer cutting gearbox. *J. Vib. Shock.* **2019**, *38*, 179–184+196.
162. Han, L.M. Fault analysis and diagnosis of key components of shearers. *Energy Conserv.* **2021**, *11*, 156–157+159.
163. Achanti, V.B.; Khair, A.W. Cutting efficiency through optimized bit configuration-an experimental study using a simulated continuous miner. *Miner. Resour. Eng.* **2001**, *10*, 427–434. [CrossRef]
164. Peng, T.H.; Li, C.P.; Zhu, Y.M. Design and application of simulating cutting experiment system for drum shearer. *Appl. Sci.* **2021**, *11*, 5917. [CrossRef]
165. Eshaghian, O.; Hoseinie, S.H.; Maleki, A. Multi-attribute failure analysis of coal cutting picks on longwall shearer machine. *Eng. Fail Anal.* **2021**, *120*, 105069. [CrossRef]
166. Sun, Y.; Li, X.S. Experimental investigation of pick body bending failure. *Int. J. Mech. Eng. Robot. Res.* **2018**, *7*, 184–188. [CrossRef]
167. Parshyna, O.; Parshyn, Y. Analytical platform to provide competitiveness of ore-mining machinery manufacturing. *Min. Miner. Depos.* **2020**, *14*, 61–70. [CrossRef]
168. Sun, Z.L. Research on cutters reasonable arrangement in screw drum of shearer. *Architect. Eng. Technol. Des.* **2016**, *4*, 1563.
169. Wang, S.B.; Ge, S.R.; Wang, S.J.; Li, Z.; Wan, Z.J. Development and chanllege of unmanned autonomous longwall fully-mechanized coal mining face. *Coal Sci. Technol.* **2022**, *50*, 231–243.
170. Ren, C.Y.; Yu, X.W. Drum plate pick arrangement and installation on shearer. *J. Heilongjiang Inst. Sci. Technol.* **2008**, *4*, 247–249.
171. Shao, L.B. Research on cutting tooth arrangement in screw drum of shearer. *J. Kunming Metall. Coll.* **2014**, *30*, 48–51+65.
172. Wang, Q.; Wang, L.J.; Wang, G. Approach to optimal line spacing for cutting picks of mining spiral cylinder. *J. Liaoning Tech. Univ.* **2005**, *24*, 118–120.
173. Evans, I. Line spacing of picks for effective cutting. *Int. J. Rock Mech. Min.* **1972**, *9*, 355–361. [CrossRef]
174. Wang, L.; Chen, L.J.; Guo, J.W.; Li, X.D. Arrangement optimization of cutting tooth on new thin seam shearer drum. *Mech. Eng.* **2015**, *11*, 120–122. [CrossRef]
175. Kumar, M.P.; Ramakrishna, N.; Amarnath, K.; Kumar, M.S. Study on tool life and its failure mechanisms. *Int. J. Innov. Res. Sci. Technol.* **2015**, *2*, 126–131.
176. Liu, S.Y.; Du, C.L.; Jiang, H.X. *Mechanical Water Jet Combined Rock Breaking and Its Application in Mining Machinery*; Liu, S.Y., Ed.; Science Press: Beijing, China, 2017; pp. 86–87.
177. Cheluszka, P.; Mikuła, S.; Mikuła, J. Conical picks of mining machines with increased utility properties-selected construction and technological aspects. *Acta Montan. Slovaca* **2021**, *26*, 195–204.
178. Liu, S.Y.; Du, C.L.; Cui, X.X.; Song, J. Experiment research on a new shearer drum. *Procedia Earth Planet Sci.* **2009**, *1*, 1393–1397.
179. Liu, S.Y.; Du, C.L.; Cui, X.X. Model test of the cutting properties of a shearer drum. *Min. Sci. Technol.* **2009**, *19*, 4–78. [CrossRef]
180. Liu, S.Y.; Du, C.L.; Cui, X.X. Research on the cutting force of a pick. *Min. Sci. Technol.* **2009**, *19*, 514–517. [CrossRef]
181. Qayyum, R.A. *Effects of Bit Geometry in Multiple Bit-Rock Interaction*; West Virginia University: Morgantown, WV, USA, 2003.

182. Bakar, M.Z.A.; Gertsch, L.S. Evaluation of saturation effects on drag pick cutting of a brittle sandstone fromfull scale linear cutting tests. *Tunn. Undergr. Space Technol.* **2013**, *34*, 124–134. [CrossRef]
183. Wang, X.C. *The Abrasive Resistance Study about the Cutting Picker of Coal Cutter*; Wuhan University of Science and Technology: Wuhan, China, 2011.
184. Desouza, G.N.; Kak, A.C. Vision for mobile robot navigation: A Survey. *IEEE Trans. Pattern Anal. Mach. Intell.* **2002**, *24*, 237–267. [CrossRef]
185. Li, H.S.; Liu, S.Y.; Xu, P.P. Numerical simulation on interaction stress analysis of rock with conical picks. *Tunn. Undergr. Space Technol.* **2019**, *85*, 231–242. [CrossRef]
186. Kim, E.; Hirro, K.; Oliveira, D.; Kim, A. Effects of the skew angle of conical bits on bit temperature, bit wear, and rock cutting performance. *Int. J. Rock Mech. Min. Sci.* **2017**, *100*, 263–268. [CrossRef]
187. Kim, E. Effect of skew angle on main precursor of frictional ignition in bench-scale simulation of excavation processes. *Int. J. Rock Mech. Min. Sci.* **2015**, *80*, 101–106. [CrossRef]
188. Gu, J.Y. *Pick Wear State Recognition Based on Multi-Source Heterogeneous Information and Deep Learning*; Liaoning Technical University: Fuxin, China, 2021.
189. Zhang, Q.; Liu, Z.H.; Dai, X.D.; Huang, C.H.; Zhang, S.L.; Tian, Y. Study on wear degree recognition picks based on vibration and acoustic emission signals. *Mach. Des. Res.* **2018**, *1*, 126–132.
190. Zhang, Y.T. *Numerical Simulation Research on Rock Cutting by Shearer Conical Picks*; Taiyuan University of Science and Technology: Taiyuan, China, 2018.
191. Zhang, Q.; Zhang, X.Y. Wear characteristics of shearer pick. *J. Liaoning Tech. Univ.* **2021**, *40*, 430–439.
192. Liu, Q.; Jiang, L.G.; Su, R.H. Study on the wear characteristics of the cutting teeth of the end-side spiral shearer's bit. *J. Mach. Des.* **2021**, *38*, 34–40.
193. Liu, C.S.; Song, Y.; Chen, J.G.; Sun, G.Y. Simulation of temperature fields on conical pick cutting rock. *J. Heilongjiang Univ. Sci. Technol.* **2013**, *23*, 337–340.
194. Li, W.W. Finite element analysis of the coal winning machine cutting teeth. *Mech. Res. Appl.* **2016**, *29*, 48–50+55.
195. Qin, C. *Finite Element Simulation and Remaining life Prediction of Shearer-Picking Mechanic*; Shandong University of Science and Technology: Qingdao, China, 2018.
196. Loui, J.P.; Karanam, U. Heat transfer simulation in drag-pick cutting of rocks. *Tunn. Undergr. Space Technol.* **2005**, *20*, 263–270. [CrossRef]
197. Yang, D.L.; Li, J.P.; Wang, L.P.; Gao, K.D.; Tang, Y.H.; Wang, Y.X. Experimental and theoretical design for decreasing wear in conical picks in rotation-drilling cutting process. *Int. J. Adv. Manuf. Tech.* **2015**, *77*, 1571–1579. [CrossRef]
198. Jakub, G.; Jozef, J. Towards the identification of worn picks on cutter drums based on torque and power signals using artificial neural networks. *Tunn. Undergr. Space Technol.* **2011**, *26*, 22–28.
199. Shao, W.; Li, X.S.; Sun, Y.; Huang, H. Parametric study of rock cutting with SMART*CUT picks. *Tunn. Undergr. Space Technol.* **2017**, *61*, 134–144. [CrossRef]
200. Zhang, Q.; Wang, H.J.; Li, L.Y.; Liu, Z.H. Online monitoring of shearer's pick wear based on ANFIS fuzzy information fusion. *China Mech. Eng.* **2016**, *27*, 2607–2614.
201. Zhang, Q.; Liu, Z.H.; Wang, H.J.; Huang, C.H.; Ruan, Y.X. On-line monitoring of pick's wear degrees based on BP neural network. *China Mech. Eng.* **2017**, *28*, 1062–1068.
202. Shi, D.; Gindy, N.N. Tool wear predictive model based on least squares support vector machines. *Mech. Syst. Signal Process.* **2007**, *21*, 1799–1814. [CrossRef]
203. Alber, M. Stress dependency of the cerchar abrasivity index (CAI) and its effects on wear of selected rock cutting tools. *Tunn. Undergr. Space Technol.* **2008**, *23*, 351–359. [CrossRef]
204. Tan, Y.S.; Cai, H.P.; Ma, B.D.; Zhu, W.D.; Liu, Z.X. Wear, strength and fracture of WC-Co cemented carbides used for cutter in coal mining machine. *Rare Metal Mater. Eng.* **1996**, *6*, 7–13.
205. Ren, Z.X.; Sun, H.J.; Su, F. Analysis and research of coal mining machine cutting teeth reliability. *Coal Mine Mach.* **2004**, *6*, 36–37.
206. Sun, Y.; Li, X.S. A probabilistic approach for assessing failure risk of cutting tools in underground excavation. *Tunn. Undergr. Space Tech.* **2017**, *70*, 299–308. [CrossRef]
207. Sun, Y.; Li, X.S. Modeling the property variation of diamond composite and its impact on the reliability of cutting tools. *Adv. Mater. Res.* **2012**, *565*, 448–453. [CrossRef]
208. Sun, F.X. *Dynamics Analysis and Reliability Research of Shearer Picks Based on ANSYS/LS-DYNA*; Northeastern University: Shenyang, China, 2015.
209. Guo, H.; Zhang, Y.T.; Yan, X.G. Fatigue life analysis of conical pick based on ABAQUS/FE-SAFE. *Coal Technol.* **2018**, *37*, 306–309.
210. Lu, H.; Wang, Y.L.; Yang, Z.J. Analysis and optimization on fatigue life of pick cutter for cutting drum of coal shearer. *Coal Sci. Technol.* **2013**, *41*, 100–102+106.
211. Zhang, H.D. *Research on Regulation Mechanism Based on Multiple Quality Characteristics and Manufacturing Process of Conical Pick*; Taiyuan University of Science and Technology: Taiyuan, China, 2021.
212. Qin, Y. Approaches to improve the reliability and service life of the pick. *Value Eng.* **2014**, *23*, 60–61.
213. He, L. *Study on Failure Analysis and Engineering Application of Mining Cutting Pick*; North University of China: Taiyuan, China, 2016.

214. Wang, Y.Z.; Li, Q.L.; Liu, S.F.; Wang, C.T. Review on the development of high performance materials used as cutting picks of engineering tools. *J. Zhongyuan Univ. Technol.* **2019**, *30*, 18–21.
215. Lin, H. Research on material and process of pick tooth of the shearer. *China Plant Eng.* **2020**, *22*, 79–81.
216. Johnson, L.L. Arthroscopic Abrasion Arthroplasty. *Clin. Orthop. Relat. Res.* **2001**, *391*, S306–S317. [CrossRef]
217. Chen, H.; Yang, J.G.; Li, H.Q. Microstructure and properties of Fe-based coatings on cutting pick surface formed by plasma jet surface metallurgy. *Trans. Nonferrous Met. Soc. China* **2009**, *19*, s583–s586. [CrossRef]
218. Zvonarev, I.E.; Ivanov, S.L.; Shishlyannikov, D.I. Estimation of the residual operation life period of mechanical transmissions of mining machines by means of superficial metal hardness measurement in increased wear areas of their parts. *Procedia Eng.* **2016**, *150*, 618–625. [CrossRef]
219. Zhang, N.; Ren, M.W.; Liu, P. Identification of coal-rock interface based on principal component analysis and BP neural network. *Ind. Mine Autom.* **2013**, *39*, 55–58.