MINISTRY OF EDUCATION AND TRAINING
HANOI UNIVERSITY OF MINING AND GEOLOGY

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STUDY ON THE EFFECTS OF SOME FACTORS ON LONGEVITY OF CUTTING TEETH ON THE DRUM OF SHEARER USED IN UNDERGROUND COAL MINING IN QUANG NINH AREA

SUMMARY OF PHD THESIS

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PREFACE

1. Thesis motivation:

In the field of coal mining in Vietnam, the underground coal mining method accounts for a large proportion. Rapidly growing demand for production, reducing costs and ensure the safety of workers is an urgent issue for underground coal mining, especially the underground coal mining in Quang Ninh region. One of the solutions is to step by step completing the mining technology, partly mechanization and synchronize equipment.

For the mechanization of underground coal mining, the shearer is one of three components of the synchronous mechanized group: The shearer, supporting machine, raking trough. Currently, in countries with a developed mining industry, all or one of the three above equipments have been manufactured such as Russia, Poland, China, Germany, Czech etc

The former Soviet Union and now Russia and Ukraine now produce a large number of shearer types such as: 2K-52M (applied at Vang Danh coal mine). Beside 2K-52M machine of the Soviet Union, in Vietnam there are shearer machines from China, Czech: MG200 and MG150-W1/375-W, MG170/410WD, MB12-2V2P/R-450E is used at Khe Cham Coal Company, Vang Danh, Ha Lam and some companies in -Vinacomin.

Currently, at the underground coal mines in Quang Ninh, the hydraulic rig is applied in combination with the shearer to mechanize the mining process. However, the scope of application is still limited due to many reasons such as complicated geological conditions, type of mining, investment capacity, social conditions, etc., in which technical conditions play an important role.

There have been a number of studies and selection of shearers suitable for underground coal mining in Quang Ninh, such as Khe Cham mines, Ha Lam, Quang Hanh, Nam Mau, Vang Danh etc. However, these studies only mention of productivity and mining geological conditions. In order to increase the cutting productivity and the longevity of the shearer, the cutting module plays an important role. However studying the effect of some factors to longevity of cutting drum of shearer using in underground coal mining in Quang Ninh in order to increase productivity, increase the llongevity of the cutters and the machine, as reference for planning exploitation, investment and spare parts of pit mining process, so far which has not been interested in research.

Therefore, the PhD student proposes the project: *"Study on the effects of some factors on the longevity of cutting teeth on the drum of shearer used in underground coal mining in Quang Ninh area"* as a research topic of the doctoral thesis, in order to meet the requirements of production reality, with scientific and practical significance.

2. Research objectives

2.1. Overall objectives

Studying, analyzing and evaluating the basic factors affecting the wear resistance of the shear cutting drum, such as coal strength, the geometry of the cutting teeth, materials of cutting teeth, the cutting angle. Cutting depth, cutting feed and cutting speed are the basis for selecting the appropriate factors in fabrication, using the cutting teeth of the shearer.

2.2. Research goal

Unravel the rules and wearing mechanism of cutting drum of the shearer, thereby setting up an optimal set of cutting parameters for the purpose of improving the longevity of cutting drum.

3. Object and scope of the study

- Object: Tangent cutting teeth using on shearer.
- Scope of the study: The effects of cutting angle, cutting depth, cutting step and cutting speed of tangential cutting teeth on the longevity of cutting teeth installed on the drum of the shearer used in underground coal mining in Quang Ninh..

4. Research Methodology

- Theoretical studying in combined with experimental study.
- Studying the theory of breaking rock and coal with cutting tools and cutting tool wear mechanism.
- Experimental study according to Taguchi method and verification.

5. The scientific and practical significance of the thesis

- A regression model describing the relationship of the input factors (cutting angle, cutting depth, cutting step, cutting speed) with wearing rate of cutting tool (4.1) which has been built based on calculated data and references from studies on shearing machines, combined with the Taguchi experimental design methods and computational and statistical softwares.

- Proposing a set of parameters to optimize the wearing resistant such as: cutting angle 55^o, cutting depth 30 mm, Cutting step 28 mm, and cutting speed 1 m/s.

- Approached results can be used in calculating the design and selecting the appropriate cutting teeth for different mine geological conditions which ensure the durability of the cutting teeth. The result also can be refference documented in teaching and research.

6. Thesis defended items

The First item: Selecting the main factors affecting the wearing resistance of cutting teeth of shearing machine (cutting angle, cutting depth, cutting step and cutting speed) based on result of researching on geological characteristics of Quang Ninh region and process of breaking rock, coal by cutting teeth.

2nd item: Design experiment, perform experiment, analyze experimental results and build a regression model describing the relationship of the selected influencing factors. From there, proposing parameters for optimal wearing rate: cutting angle 55^0, cutting depth 30 mm, Cutting step 28 mm, and cutting speed of 1 m/s.

7. The novelty of the thesis

Proposed a method for determining the longevity of cutting teeth based on wearing rate, mean while determine optimal parameters: cutting angle 55^o, depth of cut 30 mm, Cutting step 28 mm, and cutting speed of 1 m/s.

8. The volume and structure of the thesis

The thesis includes the preface, 4 chapters, conclusions, recommendations, list of published works of the author, references and appendix. The entire content of the thesis is presented in 124 pages on A4 size paper, size 14, Time New Roman font, including 22 tables and 61 pictures.

CHAPTER 1
OVERVIEW OF TANGENT CUTTING TEETH INSTALLED ON COAL SHEARING MACHINES USED IN UNDERGROUND COAL MINING

1.1 Overview of tangent cutting teeth

Tangential cutting teeth was first produced in 1970s. The advantage of this cutting teeth type is able to self rotate while working, therefor cutting teeth is uniform worn and have self-sharpening. The remarkable point is that the placement of cutting teeth in the tangent direction with the cutting trajectory will reduce the axial deviation of the supporting part because the drag force acting on the teeth is mainly the compressed force. Therefore, the durability and longevity of the cutting teeth and tooth brackets is increasesed because the shank is subjected to compressed instead of bended. The tangential cutting tests conducted at mines in Russia, USA, Poland etc showed that the consumption of cutting teeth decreased by 5-10 times in compare with the use of radial cutting teeth.

The tangential cutting teeth may have different characteristics depend on the manufaturers, however their coposition characteristics are the same. The tangent cutting teeth have a symmetrical structure, including the head part (2) and the tail part (4) (Figure 1.1). The alloy head is welded tightly or pressed to the top of the cone (2). The cutting teeth can be freely rotated in the base of tooth (3) and braked by the brake (5). The brake prevents teeth from falling out during operation. Because in cutting process, cutting force acting on the side of teeth is not equal, leads to rotational torque makes cutting teeth rotate freely in the base (3). This design contributes to maintaining the geometry of the cutting teeth for a long time, increase the life of the tooth.

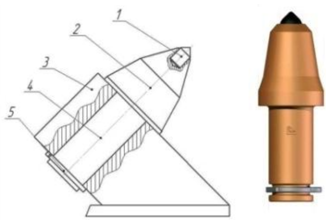


Figure 1. 1 New structure of teeth tangent rotating cutting on the base

The size and shape of the cone and the alloy head of cutting teeth will differ due to geological conditions (Figure 1.2 and 1.3).

a, b,

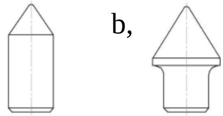


Figure 1.2 - Cylindrical alloy cutting head (1.2a) and mushroom-shaped alloy cutting head (1.2b)

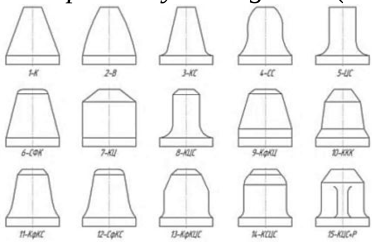


Figure 1. 3 Shape of the cone part of tangent cutting tooth

1.2 The research of tangential cutting teeth in Vietnam and in the world

In addition to the Soviet 2K-52M shearer, currently in Vietnam, Chinese and Czech shearers are used such as: MG200-W1 and MG150/375-W, MG170/410WD, MB12-2V2P/R- 450E. These shearer is used at Khe Cham Coal Company, Vang Danh, Ha Lam and some companies in -Vinacomin.

The machines manufactured by foreign countries have been brought into Vietnam for many years, due to many reasons such as geological conditions, mine pressure, seam inclination angle, seam thickness, capacityof seam that can be mechanized, affecting the efficiency, productivity and longevity of machine.

During the working process, the cutting teeth of the shearer operate under high compressive and bending force, continuous changing load conditions. So cutting teeth is a part that often breaks down. Moreover, the manufacturing of cutting teeth in Vietnam is limited and fragmented, only made according to the model without any reliable research or evaluation. The domestically manufactured cutting teeth are cheaper, but the longevity is very low in compared to the imported teeth, thus causing the coal production cost to increase. So, domestic cutting teeth are rarely chosen by users. Therefore, the study of geometrical factors and cutting modes affecting the longevity of the cutting teeth of the shearer in Vietnamese underground coal mines is considered urgent in the current period.

1.2. 1. **The research of tangential cutting teeth in the world**

Research results indicate that:

- When cutting the rock has medium solidity (f = 4 ÷ 6), the main cause of damage to cutting teeth is the abrasive of head cone of body of cutting teeth, cutting force on the tip of cutting teeth (the hard alloy tip) is large leads to deformation and increasing the gap between the cutting tip and the body of the tooth, resulting in the cutting tip loosening or breaking. The replacement cutting teeth account for 10-30% of the total cost of mining;

- By testing with medium hardness rock, it is determined that increasing the hardness of the body will reduce the wear rate of cutting teeth;

- Research results have shown that creating local hardening zones by applying thermomechanical treatments significantly increases the wearing resistance of cutting teeth (up to 1.9 times);

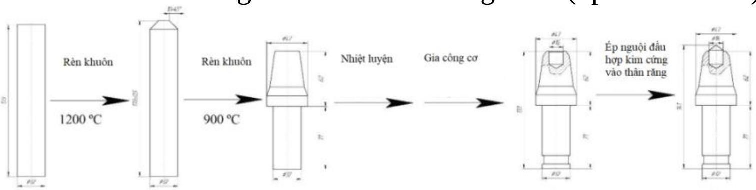


Figure 1. 4 Technological process for the production of cutting teeth by pressure machining

- Using the finite element method to study the deformation of the cutting teeth in the working condition (Figure 1. 5).

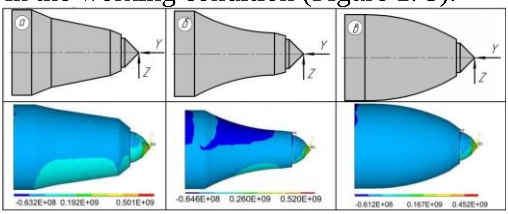


Figure 1. 5 Stress change in Cutting teethwith lateral change of cutting crown

1.2.2 **The research of tangential cutting teeth in Vietnam**

It can be seen that the research on coal shearing machines, cutting teeth for shearer is just stop at study of the selection of synchronous equipment, application conditions and some basic parameters of cutting teeth. Fully study the influence of technological parameters, working modes (cutting angle, cutting depth, cutting step, cutting speed, etc) on wearing resistance as well as life time of cutting teeth and machine has not been done.

Remarks :

- The geological condition of some underground coal seams in Quang Ninh is very complicated in the multi-layered rock with a solidity *f* from 4 to 7, greatly affecting the wearing resistance of the cutting teeth;
- The research results of the shearer just stop at the selection for a specific mine, have not been payed attention to the life of cutting teeth and the synchronization in the mechanization of underground coal mining;
- Along with the development of science and technology in Vietnam, the author found that it is completely possible to conduct research, calculate, design and manufacture the machineries of the cutting parts with the quality asymptotic to the quality of the imported cutting teeth.

CHAPTER 2
THEORY RESEARCH ON STONE AND COAL CUTTING AND WEARING MECHANISM OF CUTTING TOOLS

2.1 Study on the mechanism of the destruction of rock and coal by cutting teeth

In the process of making the shearing machine, the cutting tool (cutting teeth) cuts the coal layer by layer from the coal block. This process is considered cyclical and hops due to the brittleness of the broken material. In which the breaking process consists of 2 main stages: crushing and breaking (figure 2. 1).

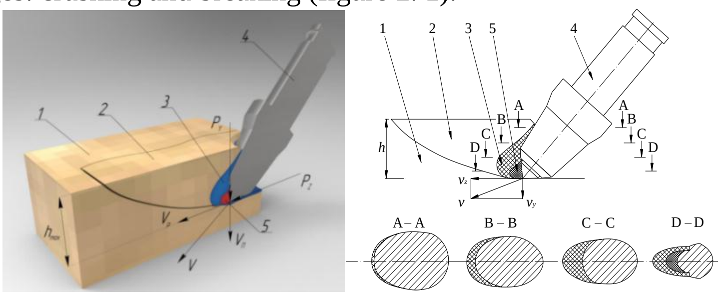
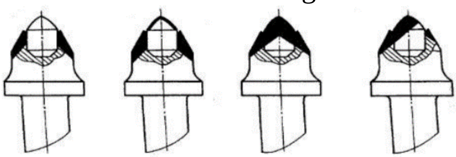


Figure 2. 1 Working diagram of cutting teeth in coal seams
1 – Coal block; 2 - Elastic deformation zone; 3 – Elastic fracturer zone; 4 – Cutting tooth; 5 – Local crushing zone

Cutting begins when cutting teeth 2 moves the crushed rock in front of cutting teeth tip (zone 5) and spreads to surrounding areas (elastic deformation zone 2) through elastic fracture zone 3. Cracks are formed, breaking the natural texture of the coal layer with the coal block, then the coal layer is completely separated from the coal block.

2.2 Analysis of Cutting teethfailure mechanism due to abrasion phenomenon

From the mechanism of destroying rock via cutting teeth, it can be seen that the contact stress on the Cutting teethwill gradually decrease from the top of the hard alloy to the cutting tooth. With the analysis of the structure and Cutting teethmaterial, it is found that the tip materials are usually made of high hardness alloys (≥ 70 HRC), the base materials are usually 30XM, 40X, 40XM, etc has a hardness of 54 HRC, much lower than that of a hard alloy. However, the contact pressure between it and rock is very large. Thus, it is easy to see that the most vulnerable area is the metal surrounding the hard alloy.



a, b, c, d,

Figure 2. 2 Corrosion patterns of cutting tooth

According to the research results, cutting tooth damaged by abrasion will have the following phenomena:

- Cutting tooth working with coal seams without clamping rock (solidity $f = 0.8 \div 1.5$) with small amount of cutting teeth wearing, almost hard alloy tip is not abrasive. The Cutting teeth is worn around the hard alloy tip until it weakens the bond between the base and the hard alloy tip (Figure 2.2 -a), leading to the loss of the hard alloy tip, the wearing process is very slow. The consumption of cutting teeth is only 0.5 ÷ 2 teeth/1000 tons of coal;

- Cutting teeth working with seams of medium strength (coal with solidity $f = 2 \div 5$), hard alloy tip is abrasive but the amount of wear is small, however the steel surrounded alloy tip is weared faster (Figure 2. 2 -b), leads to weakening its link with alloy head and quickly losing the hard alloy tip. The consumption of cutting teeth is from 12 to 50 teeth/1000 tons of coal;

- Cutting teeth working with highly strength seams (coal with solidity *f* = 5 ÷ 10), cutting teeth is weared at both tip and tip holder (figure 2. 2 -c, d). The researches have shown that when teeth working with rock has high solidly (compressive strength of 120 MPa (equivalent *f* = 12) with cutting speed v = 2.5 m / s, cutting depth h = 10 mm, t = 50 mm Cutting step) temperature at the surface of the teeth and exposed rocks rising rapidly can reach over 1100 ˚C (see figure 2. 3) may melt the metal, in addition to the ignition phenomenon occurs, which is dangerous to mining safety conditions.

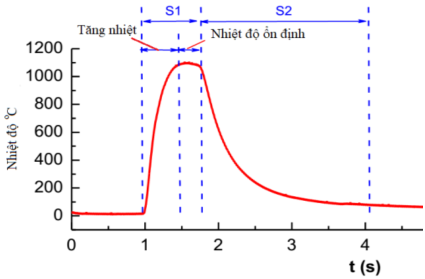


Figure 2. 3. Histogram of the temperature rise on the surface of the Cutting teethduring work

2. 3 Analysis of tooth failure mechanism according to destructive conditions

The phenomenon of tooth failure due to overload usually occurs in cases of faulty teeth when manufacturing (defects during machining or heat treatment), the calculation of cutting teeth selection is not suitable for the geological conditions of the mine. More common, due to the combination of abrasion and high load when encountering clamped rock is the main cause of rapid tooth failure. If a cutting tooth broken, the next cutting tooth on a cutting line would will have to cut a thicker layer of rock, which means that the cutting force on it will spike, overloading it and causing it to fail faster. Therefore, determining parameters such as the maximum height of the alloy protruding part and the minimum depth of the alloy tip located in the crown will help improve the longevity of the cutting teeth. Thus, we can predict the longevity of cutting teeth.

The cutting force exerted on the cutting teeth can be determined by the formula:

$$Z_{cb} = \frac{A.(0{,}35.b + 0{,}3)}{b + h_{tb}.tg\theta}.h_{tb}.t_{tb}.k_t.k_g.k_a.k_\theta.\frac{1}{\cos\beta}, \text{ N}; \quad (2.5)$$

Where: A – Unit shearing force of coal, A = 2410 - 3000 N/cm; b - width of cutting teeth, b = 0.8 cm; h_{tb}- Average cutting thickness of the primary cutting teeth, cm ; t_{tb}- Average cutting width of cutting teeth, cm; k_t- Mirror exposure factor, k_t= 1.1 ÷ 1.25, k_t= 1.2 is selected; k_g- coefficient of the cutting angle, k_g= 0,98; k_a- Coefficients taking into account the impact of mining pressure, k_a= 0.56; k_θ- Coefficient taking into account the pre-cut shape of cutting teeth, k_θ= 0,92; β - The teeth mounting angle with the moving direction of the working part, degree; θ - The broken angle of coal, degree.

Shearing force P and bending force N are determined as:

$$P = Z_c \cdot Sin\theta \text{ and } N = Z_c \cdot Cos\theta \quad (2.1)$$

Where: Z_c- Shearing force exerted on the cutting teeth, kN; θ - Cutting angle, degree.

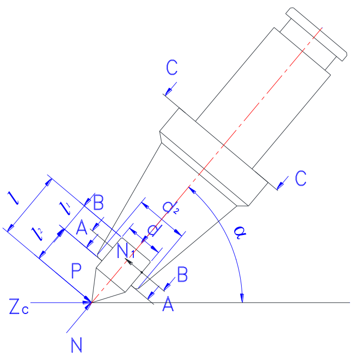


Figure 2. 4 Diagram of load distribution on cutting teeth

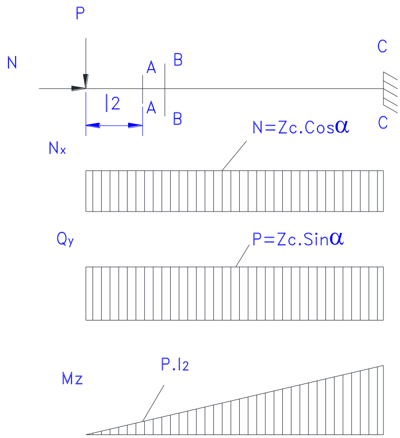


Figure 2. 5 Internal force diagram of cutting teeth

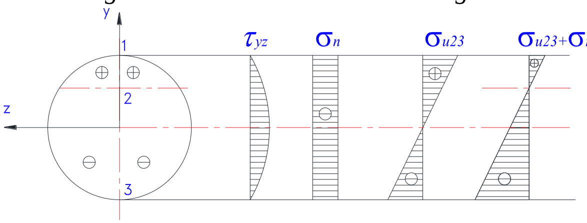


Figure 2. 6 Diagram of internal force on cross section of cutting teeth.

To ensure durable conditions:

With point 1 (Figure 2. 6): compressive stress must be less than allowable compressive stress $\sigma_{td1} \le [\sigma_n]$;

With point 3 (Figure 2. 6): tensile stress must be less than allowable tensile stress $\sigma_{td2} \le [\sigma_k]$.

l_2 is determined according to durable conditions :

$$\sigma = \frac{M}{J_x} \cdot y - \frac{N}{F} \le [\sigma_u] \Leftrightarrow l_2 \le \frac{d^3}{5 \cdot Z_c \cdot Sin\theta} \cdot [\sigma_u] \quad (2.\ 2)$$

The minimum length l_1 is determined according to the fourth theory (at cross-section BB)

$$\sigma_{td\max} = \sqrt{\sigma_r^2 + \sigma_t^2 - \sigma_r \cdot \sigma_t} \le [\sigma_u] \quad (2.3)$$

Where:

Normal stress:

$$\sigma_r = \frac{d^2}{d_2^2 - d^2} . \left(1 - \frac{d_2^2}{d^2}\right) . \frac{N_1}{F} \quad (2.\ 4)$$

Tangential stress:

$$\sigma_t = \frac{d^2}{d_2^2 - d^2} . \left(1 + \frac{d_2^2}{d^2}\right) . \frac{N_1}{F} \quad (2.\ 5)$$

With: N- Force exerted on the outer metal layer of the hard alloy head, kN; F - The surrounding area of the hard-alloy head mounting hole on the cutting teeth, mm^2; d - Cutting pin diameter (alloy head), mm; d_2 - Average diameter of the enclosure of the alloy head, mm.

Solve the inequalities (2. 3) we have

$$l_1 \ge \frac{-(C \cdot l_2 - 1) + \sqrt{(C \cdot l_2 - 1)^2 - 2C \cdot l_2}}{C}, \text{ mm} \quad (2.6)$$

Where: $C = \frac{[\sigma_u]}{\sqrt{A^2 + B^2 - A \cdot B}}$

With:

$$A = 4 \cdot \frac{d^2}{d_2^2 - d^2} . \left(1 - \frac{d_2^2}{d^2}\right) . \frac{Z_c \cdot Sin\theta}{\pi \cdot d^2}$$

and $B = 4 \cdot \frac{d^2}{d_2^2 - d^2} \cdot \left(1 + \frac{d_2^2}{d^2}\right) \cdot \frac{Z_c \cdot Sin\theta}{\pi \cdot d^2}$

Therefor, to ensure cutting teeth is in normal working condition, it must satisfy both of two conditions: the length l_1 is not smaller than $l_1 \geq \frac{-(C \cdot l_2 - 1) + \sqrt{(C \cdot l_2 - 1)^2 - 2C \cdot l_2}}{C}$ and l_1 is not larger than $l_2 \leq \frac{d^3}{5 \cdot Z_c \cdot Sin\theta} \cdot [\sigma_u]$.

2.4. Determining the longevity (total cutting distance length) of the cutting teeth according to the wear resistance conditions

To accurately determine the maximum amount of metal lost due to wearing, it is needed to consider the specific case of each cutting teeth type (specific parameters of cutting teeth). The author only proposes a preliminary method to determine theoretical wearing.

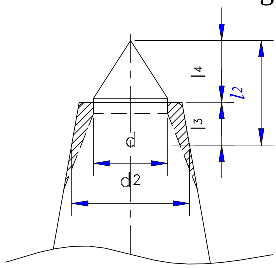


Figure 2. 7 Maximum wearing of cutting teeth

Total wearing of cutting teeth from initial to damaged is calculated by the following formula:

$$\sum m_{mon} = \frac{\pi}{4} \cdot \left(d_2^2 - d^2\right) \cdot l_3 \cdot \gamma = \frac{\pi}{4} \cdot \left(d_2^2 - d^2\right) \cdot \left(l_2 - l_4\right) \cdot \gamma \qquad (2.7)$$

Where : l_3 – maximum length of worn part, mm; d_3 - Average diameter of worn part, mm; γ- Density cutting teeth material, kg / m ^{3}.
Total percentage of maximum wearing over the life of the cutting teeth

$$\sum I_{mon} = \frac{\sum m_{mon}}{m} = \frac{\frac{\pi}{4} \cdot \left(d_2^2 - d^2\right) \cdot l_3 \cdot \gamma = \frac{\pi}{4} \cdot \left(d_2^2 - d^2\right) \cdot \left(l_2 - l_4\right) \cdot \gamma}{m} \qquad (2.8)$$

Where m - the mass of the cutting teeth, kg.
The total service length over the life of the cutting teeth arcording to wearing resistance conditions can be determined as follows:

$$S = \frac{\sum I_{mon}}{I_h} \tag{2. 9}$$

Where: I_h – wearing rate of cutting teeth per km.

Discussion

- By studying and analysis of geological structural characteristics of the coal seams in Quang Ninh, it showed that the solidity of coal and rock in the coal seam ranged from f = 0.3 to f = 7.06. Therefore, the selection of the research scope of clamped rock and representative coal is an important factor determining the results of the study on the wearing resistance of coal cutting teeth in the direction that is close to reality and ensures the reliability, high economy.

- A method for determining the maximum length of the alloy head protruding from the base (2.2) and the minimum length of the alloy head surrounded by the base (2.6) has been developed. From there, determine the life of the cutting teeth according to the wearing resistance condition (2.8 and 2.9).

- The above results create a scientific basis for the construction of the experimental method; experiment and evaluating the effects of a number of technological factors such as cutting depth, Cutting step, cutting angle, cutting speed on the wearing resistance of the cutting teeth on shearer.

CHAPTER 3
EXPERIMENTAL PLANNING TO ASSESSMENT OF WEARING RESITANCE OF CUTTING TEETH ON SHEARER

3.1. Selecting the input parameters for the experiment to evaluate the reliability of cutting teeth

The cutting angle, cutting depth, the distance of two adjacent cuts and cutting speed of the cutting teeth are selected as input parameters for the experiment to evaluate the wearing resistance of the cutting teeth of shearer.

Table 3.1 Input parameters

Parameter	Symbol	Unit	Value according to the degree of the factors				
			first	2	3	4	5
Cutting angle	θ	Degree	45	50	55	60	65
Cutting depth	H	mm	30	35	40	45	50
Cutting step	S	mm	28	36	42	48	54
Cutting speed	v	m / s	first	1.5	2	2.5	3

3.2 Taguchi methodology

Parameters: cutting depth, cutting angle, cutting step and cutting speed are selected as the input variables of the experiment. With 5 levels and 4 orthogonal elements L25 is used to plan the implementation of the experiment. The experimental arrangement for the cutting parameters using the L25 Taguchi orthogonal array is shown in Table 3.2. By the manipulation of matrix orthogonal design of Taguchi, the experiment required has been reduced from 625 (5^4) to 25 experiments, thus significantly reducing the cost, time and effort performance man.

Table 3. 2 Experimental design with the L25 orthogonal array of Taguchi

Experiment	A (θ□)	B (h)	C (s)	D (v)
1	45	30	28	1
2	45	35	36	1.5
3	45	40	42	2
4	45	45	48	2.5
5	45	50	54	3
6	50	30	36	2
7	50	35	42	2.5
8	50	40	48	3
9	50	45	54	1
10	50	50	28	1.5
11	55	30	42	3
12	55	35	48	1
13	55	40	54	1.5
14	55	45	36	2
15	55	50	36	2.5
16	60	30	48	1.5
17	60	35	54	2
18	60	40	28	2.5
19	60	45	36	3
20	60	50	42	1

21	65	30	54	2.5
22	65	35	28	3
23	65	40	36	1
24	65	45	42	1.5
25	65	50	48	2

3. 3. Constructing a regression function

In this study, the mathematical function shows the relationship of the cutting parameters to the wearing rate, allowing to predict the desired value based on the cutting parameters in the permissible range. In this thesis, using the multi-target optimization method by MRWSN, polynomial regression, which takes into account the interaction between theoretical cutting parameters by Gauri. The mathematical model looks like:

$$\begin{aligned} Y &= a_1 + a_2x_1 + a_3x_2 + a_4x_3 + a_5x_4 + a_6x_1x_2 + a_7x_1x_3 + a_8x_1x_4 + a_9x_2x_3 \\ &+ a_{10}x_2x_4 + a_{11}x_3x_4 + a_{12}x_1x_2x_3 + a_{13}x_1x_2x_4 + a_{14}x_1x_3x_4 + a_{15}x_2x_3x_4 + a_{16}x_1x_2x_3x_4 \end{aligned} \quad (3.1)$$

Where:

Y - Function representing the output property to be considered *(shearing strength, wearing rate) ;*

$a_1, a_2, ..., a_{16}$ - the coefficients of the equation ;

x_1, x_2, x_3, x_4 - Experimental variables *(factors affecting wearing resistance of cutting tip).*

Applying transformations we get the following canonical form:

$$\begin{cases} \sum_{i=1}^{n} Y_i = a_1\sum_{i=1}^{n} 1 + a_2\sum_{i=1}^{n} x_{1i} + ... + a_{15}\sum_{i=1}^{n} x_{2i}x_{3i}x_{4i} + a_{16}\sum_{i=1}^{n} x_{1i}x_{2i}x_{3i}x_{4i} \\ \sum_{i=1}^{n} x_{1i}Y_i = a_1\sum_{i=1}^{n} x_{1i} + a_2\sum_{i=1}^{n} x_{1i}^2 + ... + a_{15}\sum_{i=1}^{n} x_{1i}x_{2i}x_{3i}x_{4i} + a_{16}\sum_{i=1}^{n} x_{1i}^2x_{2i}x_{3i}x_{4i} \\ ------------------------------ \\ \sum_{i=1}^{n} x_{1i}x_{2i}x_{3i}x_{4i}Y_i = a_1\sum_{i=1}^{n} x_{1i}x_{2i}x_{3i}x_{4i} + a_2\sum_{i=1}^{n} x_{1i}^2x_{2i}x_{3i}x_{4i} + ... + a_{15}\sum_{i=1}^{n} x_{1i}x_{2i}^2x_{3i}^2x_{4i}^2 + a_{16}\sum_{i=1}^{n} x_{1i}^2x_{2i}^2x_{3i}^2x_{4i}^2 \end{cases}$$

(3.2)

Solve the equations 3.2 with variables of mathematical equations by Newton - Raphson on Minitab. Based on that basic, building a mathematical equation representing the relationship of research parameters (cutting angle, cutting depth, cutting step, cutting speed) with the defined output properties (wearing rate).

3. 4 Set up an experiment

3. 4.1 Design of experimental equipment

Testing device is constructed from upper frame 1 mounted on lower frame 7. The upper frame and lower frame can slide along the o *x* axis. Frame 1 is fastened to sprocket 10, chain 10 is driven by an 8-speed stepper motor that pulls the frame 1 move. On the upper frame, there is a servo motor 12 with direct drive for the cutting plate. 4. Motors 8 and 12 are continuously controlled by AC Spindle Drives control system.

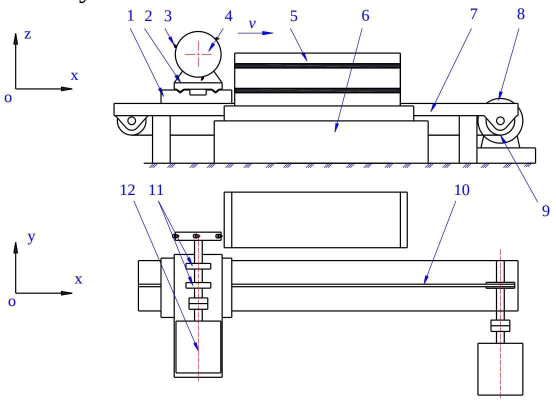


Figure 3. 1 Diagram of experimental equipment
1 - Upper frame; 2 - Guide bar 3 - Cutting teeth; 4- Cutting plate; 5 - Sample; 6 - Cutting table; 7 - Lower frame; 8 - The motor drives the movement; 9 - Chain machnism; 10 - The chain; 11 - Bearing; 12 - The motor drives the cutting drum

3. 4. 2. Experimental cutting teeth

- Teeth type: use tangent cutting teeth,
- Shape: similar to the cutting teeth on some shearer used in underground coal mining in Quang Ninh.

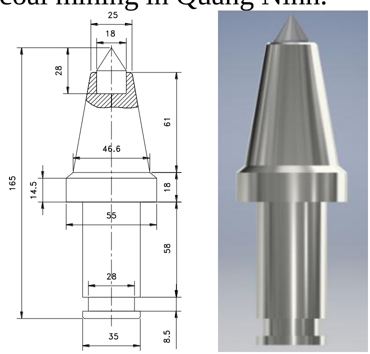


Figure 3. 2 Shape of cutting teeth used for testing

- Structure of cutting teeth includes two main parts:

* The body of teeth: made by 40X alloy carbon steel, with ultimate strength δ_b = 980 MPa; yield strength δ_{ch} = 785 MPa; ultimate compressive strength δ_n = 500 MPa; density 7.85 g/cm$^{3.}$

* The cutting tip: made by hard alloy WC group (WC08, BK8), which has ultimate strength δ_b = 1600 MPa.

After completing the preparatory work, experiments have been carried out. It should be noted that cuts near the edge of the sample should be removed from the analysis as these tests can cause unreliable forces and unreliable mass broken sample.

Discussion: In chapter 3, materials, equipment and experimental methods have been selected. Specifically, the testing sample with properties almost similar to rock, coal in the Quang Ninh area has been setup. Building experimental model to meet the requirements for testing process and experimental methods according to Taguchi, etc creating a basis for experimentation, determining methods of evaluating the effects of factors on longevity of the cutting teeth on the cutting drum used in underground coal mining in Quang Ninh.

CHAPTER 4
ANALYSIS OF RESULTS AND DISCUSSION

4. 1 Experimental results

From experiment and theoretically proved that wearing resistance is considered the most important criteria in evaluating the durability of the cutting teeth. Thus, obtained results have important significance in assessing the impact of these factors to the longevity of teeth [58]. The results obtained from the rock cutting experiments are shown in Table 4.1. With the Taguchi method, the loss function is converted to signal-to-noise (S/N) ratios that are used to measure the quality characteristic deviating from the desired values. Since the minimum values of the wearing are preferred during the cutting process, the quality characteristics *yi* required to reach as small as possible are preferred in this study. The S/N ratio is shown in table 4.1.

Table 4. 1 Wearing rate and corresponding S/N ratio

Experi-ment	Experimental results		Experi-ment	Experimental results	
	$I_{h,}$%	S/N (dB)		$I_{h,}$%	S/N (dB)
1	0.120	18.416	14	0.141	17,016
2	0.145	16,773	15	0.184	14,704
3	0.172	15,289	16	0.115	18,786
4	0.243	12,288	17	0.132	17,589
5	0.274	11,245	18	0.131	17,655
6	0.135	17,393	19	0.197	14,111
7	0.196	14,155	20	0.161	15,863
8	0.237	12,505	21	0.131	17,655
9	0.178	14,992	22	0.181	14,846
10	0.159	15,972	23	0.128	17,856
11	0.139	17,140	24	0.174	15,189
12	0.122	18,273	25	0.19	14.425
13	0.142	16,954			

4.2. Determining the optimal cutting conditions

Average S/N ratio of each factor in the different testing levels are taken by the average S/N ratio of the corresponding levels. For example, the average S/N ratio for the cutting angle at level 1 is determined by averaging S/N ratio for tests 1-5 in Table 4.1. The average S/N ratio for the cutting depth at level 1 was calculated by averaging the S/N readings of experiment 1, 6, 11, 16 and 21. Average S/N ratio for other factors at different levels are calculated in the same way. All of these average S/N ratios give the corresponding S/N values, as shown in Figure 4.1, which represent the corresponding S/N values for the wearing rate.

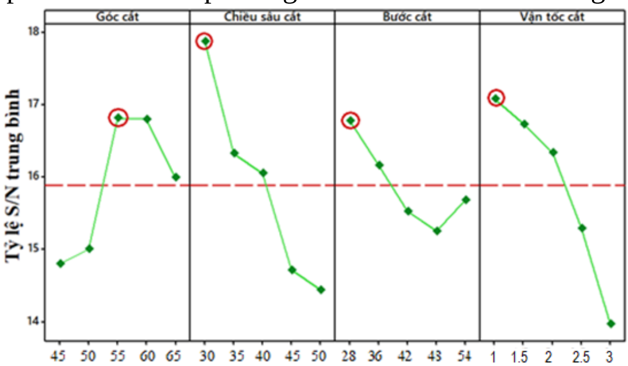


Figure 4. 1 Diagram of average S/N wearing rate ratio

In Figure 4.1, the S/N ratio of wearing rate is minimum at cutting angle 55^o (level 3), cutting depth 30 mm (level 1), cutting step 28 mm (level 1) and cutting speed of 1 m/s (level 1). Therefore, the optimal parameter combination for wearing rate is A3B1C1D1.

4.3. Variance analysis (ANOVA)

The results of ANOVA for wearing rate are shown in Table 4. 2 respectively. Contribution percentage of each cutting parameter to wearing rate is shown in Figure 4. 2.

Table 4. 2. ANOVA results for wear intensity

Factor	DF	Seq SS	Adj SS	Adj MS	F ratio	P	Influence level (%)
Cutting angle	4	18,345	18,345	4.5861	11.30	0.002	18.5
Cutting depth	4	38,189	38,189	9.5471	23.53	0.000	38.6
Cutting step	4	7.231	7.231	1.8077	4.45	0.075	7.3
Cutting speed	4	31,909	31,909	7,9772	19.66	0.000	32.3
Error	8	3.246	3.246	0.4058			3.3
Total	24	98,919					100.00

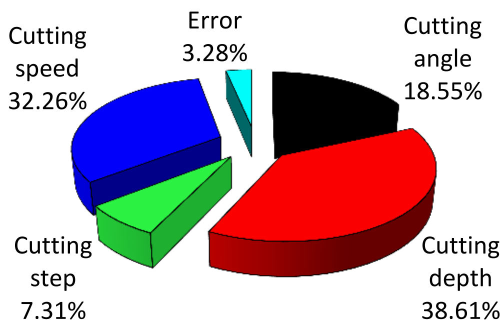


Figure 4. 2. Influence of parameters A, B, C, D on wearing rate

From the wearing rate data analysis (Table 4. 2) and Figure 4.2, as it can be seen, only the depth of cut, cutting speed and cutting angle on statistical significance on wearing rate. The cutting step is insignificant because the P value of these factors exceeds 0.05. The contribution order of the cutting process factors is cutting depth, cutting speed and cutting angle, cutting step affecting wearing rate is 38.61%, 32.26%, 18.55% and 7.31% respectively.

4.4. Effect of cutting parameters on the cutting result

The influence of the main cutting parameters on the values of wearing rate is shown in Figure 4.3. As it can be seen that, the wearing rate decreases rapidly as the cutting angle increases, reaching the minimum value at the cutting angle is 55°, then the wearing rate starts to increase with increasing cutting angle. As the cutting depth increases, the cutting step and the cutting speed increase wear strength wearing rate.

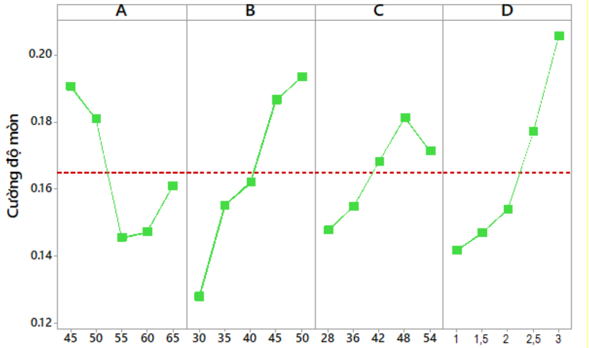


Figure 4.3. Effects of cutting and operating parameters on wearing rate (dashed red line denotes mean values)

4.5. Building regression models

The statistical methods of linear regression that have been widely used for prediction in mining and tunneling techniques are applied to develop experimental models of the wearing rate of the cutting teeth.

4.5.1 Multivariate linear regression

In this study, many linear regression models were built to predict the relationship between the wearing rate from independent variables such as cutting depth, cutting angle, cutting step and cutting speed. Equation (4.1) modeling the wearing rate was obtained using Minitab.

Polynomial regression model of wearing rate:

I_h = 4.61833 - 0.0853666*θ - 0.116005*h - 0.091763*s - 1.87565*v + 0.00229*θ*h + 0.00169*θ*s + 0.034102*θ*v + 0.002526*h*s + 0.042443*h*v + 0.04185*s*v –0.00005*θ*h*s- 0.000809*θ*h*v – 0.000967*h*s*v - 0.000749*θ*s*v +0.000018*θ*h*s*v

Where I_h is wearing rate θ, h, s and v denote the cutting angle, cutting depth, cutting step and cutting speed respectively.

From equation (4.1), using Matlab software to draw graphs in 3D, reflecting the influence of the factors on the wearing rate of cutting teeth as shown in Figure 4.4 to Figure 4.9.

Figure 4.4 shows that the wearing rate increases with increasing depth of cutting and cutting angle. The phenomenon of this can be explained as: when cutting depth is decreased, then the body of cutting teeth (hardness less than the tip) exposed rocks decreased lead to decreasing pressure acting on cutting teeth and reducing the wearing rate. When increasing the cutting angle, leading to the expansion of the compressed rock in front of the cutting teeth (hard core), then this hard core is an intermediate component encapsulating the cutting tooth, transmitting the destructive force to the rock thus reducing the wear rate.

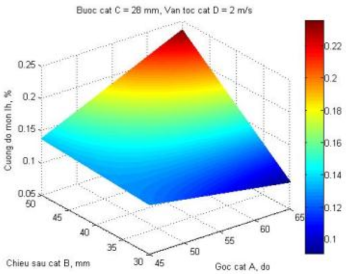


Figure 4. 4. Influence of cutting angle, cutting depth on the ware rate of tip of cutting teeth

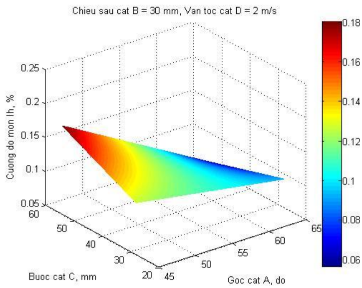


Figure 4. 5. Influence of cutting angle, cutting step to wear rate of the tip of cutting teeth

Figure 4.5 shows the smallest wearing rate when the cutting depth and cutting angle are minimum.

Figure 4.6 shows the cutting speeds increase making the intensity erosion accelerated this phenomenon can be explained as: increasing speed of cutting teeth make particular temperature of the surface cutting teeth quickly increased becaused of friction between the rock and the working surface of the cutting teeth increases rapidly but has not yet diffused into the body, seriously affecting the durability of this outer material, leading to a rapid increase in wearing rate.

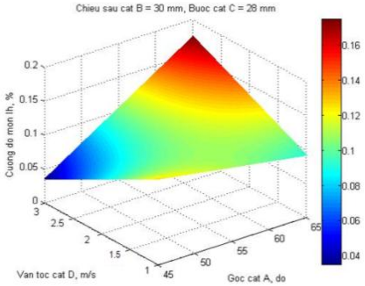


Figure 4. 6. The influence of cutting angle, cutting speed on the strength of Cutting teethwear

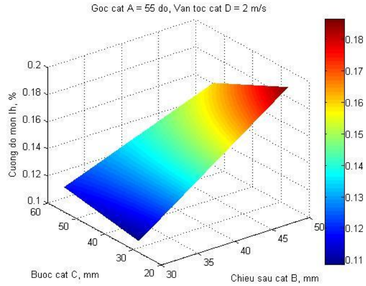


Figure 4. 7. Influence of cutting depth, cutting step on cutting edge wear intensity

From the graph Figure 4.7 shows that the waering rate increases very quickly when cutting step is reduced and cutting depth increases, now the cutting mode switches to wrap cutting. So when designing, it is necessary to optimize the ratio between the depth of cut and the cutting step.

Figure 4.8 shows that when the cutting teeth work at the speed of 1 m/s, cutting depth does not affect the wearing rate that much. Similarly, when the cutting depth is 28 mm, velocity was also shown to have no significant effect. However, when the cutting speed and cutting depth increase, the wearing rate increases dramatically.

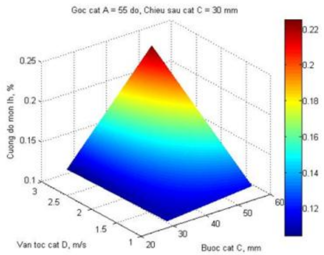


Figure 4.8. Influence of cutting step, cutting speed on the wearing rate of tip of cutting teeth

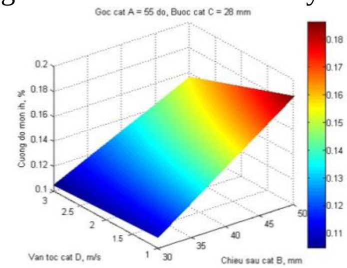


Figure 4.9. The influence of cutting depth, cutting speed on the wearing rate of tip of cutting teeth

Figure 4.9 shows that when the depth of cutting increases, the wearing rate increases rapidly. But when cutting step of 28 mm, the cutting speed also showed no significant effect.

Discussion

Using the Taguchi experimental method brings advantages: small number of experiments, but still possible to evaluate the effects of the parameters and working modes of the cutting teeth such as: cutting angle, cutting depth, distance and cutting speed to the durability of the cutting teeth.

The cutting parameters are optimized to minimize the wearing by the results obtained based on medium S/N ratio.

The parametric combination for optimum wearing rate is: cutting angle 55^o, cutting depth 30 mm, cutting step 28 mm, and cutting speed of 1 m/s.

The results obtained from the Taguchi experimental are basically similar to the obtained results by other research methods, such as: The higher cutting depth and higher the cutting speed would result in higher wearing rate.

From ANOVA analysis, it shows that: for wearing rate, three factors are statistically significant with the order of importance being: cutting angle> cutting depth> cutting speed. The cutting step has the least effect.

- Built a polynomial regression model for wearing rate

I_h = 4.61833 - 0.0853666*θ - 0.116005*h - 0.091763*s - 1.87565*v + 0.00229*θ*h + 0.00169*θ*s + 0.034102*θ*v + 0.002526*h*s + 0.042443*h*v + 0.04185*s*v –0.00005*θ*h*s- 0.000809*θ*h*v – 0.000967*h*s*v - 0.000749*θ*s*v +0.000018*θ*h*s*v

Where : I_h is wearing rate θ, h, s and v denote cutting angle, cutting depth, cutting step and cutting speed respectively.

- The research results can be used in designing and selection of cutting teeth of the coal shearing machine working in harsh conditions, but still satisfying the criteria to ensure the durability of the cutting teeth of the shearer used in pit mining in Vietnam.

GENERAL CONCLUSION

Researching and experimenting to evaluate the effects of some factors on the longevity of cutting teeth on the cutting drum of shearer used in pit coal mining has given the following conclusions:

1. The mechanism of breaking rock and coal with cutting tools (tangent cutting teeth) has been clarified.

2. The wearing mechanism of the cutting teeth of the cutting machine (tangent cutting teeth), the cause of the damage of the cutting teeth of the shearer also have been clarified.

3. A method for determining the maximum length of the alloy head protruding from the body (2. 2) and the minimum length of the alloy head enclosed by the body (2.6) has been developed. That is the basis to determine the longevity of cutting teeth (2.9).

4. A polynomial regression model has been built describing the relationship of the input factors (cutting angle, cutting depth, cutting step, cutting speed) with wearing rate of cutting teeth.

I_h = 4.61833 - 0.0853666*θ - 0.116005*h - 0.091763*s - 1.87565*v + 0.00229*θ*h + 0.00169*θ*s + 0.034102*θ*v + 0.002526*h*s + 0.042443*h*v + 0.04185*s*v –0.00005*θ*h*s- 0.000809*θ*h*v – 0.000967*h*s*v - 0.000749*θ*s*v +0.000018*θ*h*s*v

Where I_h is wearing rate *θ, h, s* and *v* denote the cutting angle, cutting depth, cutting step and cutting speed respectively.

5. The parameters for optimal wearing rate are given: cutting angle 55^o, cutting depth 30 mm, cutting step 28 mm, and cutting speed of 1 m/s.

6. The research results can be used in designing andselecting suitable cutting teeth in different mine geological conditions, but still ensuring the durability of cutting teeth, which can be used as materials in lectures and reference in scientific research.

LIST OF SCIENTIFIC PUBLICATIONS

1. Le Quy Chien, Nguyen Xuan Thanh, Dinh Van Chien, **Pham Van Tien,** Nguyen Chi Bao (2014), “Phương pháp tính toán một số thông số của răng cắt trên máy khấu than dùng trong khai thác hầm lò vùng Quảng Ninh”, *Vietnam Mechanical Engineering Journal,* (Issue 5, 2014), Page 54-60.
2. Le Quy Chien, Nguyen Xuan Thanh, Dinh Van Chien, **Pham Van Tien,** (2015), " Phương pháp nghiệm bền răng cắt của bộ phận cắt trên máy khấu than dùng trong khai thác hầm lò vùng Quảng Ninh ", *Journal of Science & Technology,* (No. 26 - February 2015), Page 21-25.
3. **Pham Van Tien,** Nguyen Khac Linh, (2018) “phân tích ảnh hưởng của điều kiện khai thác và địa chất vỉa than đến tuổi thọ răng cắt máy khấu”, *The scientific publication journal of graduate students and doctors,* 2018 No 1-2, p. 53-55. "**Фам Ван Тиен,** Нгуен Кхак Линь (2018), Анализ влияния горно-геологических условий угольных пластов на ресурс работы поворотных резцов очистных комбайнов, Журнал научных публикаций аспирантов и докторантов, № 1-2 (139-140), С 53-55".
4. Doan Van Giap, **Pham Van Tien,** Nguyen Khac Linh, Bui An Canh (2018), “Xác định tốc độ di chuyển hợp lý của máy khấu để tăng hiệu quả khai thác than trong điều kiện cường độ kháng cắt của vỉa than thay đổi”, *Journal of Mining and earth sciences* (Volume 59, *Issue* 1, 2018), pp. 50-53.
5. **Pham Van Tien,** Doan Van Giap, Nguyen Khac Linh (2018), "Nghiên cứu các yếu tố ảnh hưởng đến tuổi thọ của răng cắt máy khấu trong các mỏ than hầm lò Việt Nam", *National Conference on Earth Science and resources with sustainable development (ERSD, Hanoi 7-12-2018).*
6. **Pham Van Tien,** Dinh Van Chien, Nguyen Khac Linh (2018), "Nghiên cứu ứng dụng phương pháp thiết kế thực nghiệm Taguchi để đánh giá độ bền răng cắt máy khấu than dùng trong khai thác than hầm lò vùng Quảng Ninh", *Vietnam Mechanical Engineeriing Journal,* (Issue 12, 2018).