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Energy consumption and wear rate of diamond beads during operation of a diamond wire saw

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Abstract: Diamond wire saws are indispensable machines for the extraction and processing of dimension stones. The cutting speed, energy consumption and wear rate of the diamond beads are the most important factors in assessing the efficiency of a diamond wire saw. The parameters that influence the efficiency of the diamond wire saw can be divided into controlled and uncontrolled parameters. Uncontrolled parameters cannot be influenced directly and are related to the rock types and their properties such as strength, hardness and abrasiveness. Controlled parameters are related to the operating parameters and technical characteristics of the machine. The energy consumption and the service life of the diamond wire are directly related to the characteristics of the machine and the design of the diamond wire, such as the power of the drive motor, the diameter of the drive wheel, diamond grit size and the diameter of the wire. The operating parameters of the diamond wire saw, such as cutting speed, cutting surface, cutting angle, wire tension and cooling water flow, also have a significant influence. Based on previous studies, the influence of the above parameters on the consumption of energy and wear rate of diamond beads in the operation of a diamond wire saw was analyzed.

Key words: mining, dimension stone, extraction, diamond wire saw, efficiency

Utrošak energije i dijamantnih perli pri radu dijamantne žične pile

Sažetak: Danas su dijamantne žične pile nezamjenjivi strojevi u eksploataciji i obradi arhitektonsko - građevnog kamena. Brzina rezanja, utrošak energije i intenzitet trošenja dijamantnih perli najvažniji su čimbenici za procjenu učinkovitosti dijamantne žične pile. Parametri koji utječu na učinkovitost dijamantna žične pile mogu se podijeliti na kontrolirane i nekontrolirane. Na nekontrolirane parametre nije moguće izravno utjecati, a povezani su s inženjerskim svojstvima stijene poput čvrstoće, tvrdoće i abrazivnosti. Kontrolirani parametri povezani su s radnim veličinama i tehničkim karakteristikama stroja. Utrošak energije i trajnost dijamantne žice izravno će ovisiti o karakteristikama stroja i konstrukcijskim parametrima dijamantne žice kao što je, snaga pogonskog motora, promjer pogonskog kotača, veličina dijamanata i promjer dijamantne žice. Pored navedenog, značajan utjecaj imaju i radne veličine dijamantne žične pile kao što su brzina rezanja, kut rezanja, napetost žice, površina reza i količina vode za hlađenje. Na temelju dosadašnjih istraživanja, u radu je analiziran utjecaj navedenih parametara na utrošak energije i dijamantnih perli pri radu dijamantne žične pile.

Ključne riječi: rudarstvo, arhitektonsko građevni kamen, eksploatacija, dijamantna žična pila, učinak

1. INTRODUCTION

Stone sawing with a diamond wire saw is nowadays an established and widespread technology for the extraction of dimension stone. Diamond wire saws make it possible to saw different types of cuts, including vertical, diagonal and horizontal cuts. In addition, the diamond wire saw allows cutting of different types of stone, including marble, granite, limestone and other hard rocks. In combination with chain cutters, diamond wire saws are indispensable machines in the extraction and processing of dimension stone. The efficiency of the diamond wire saw in the quarrying of dimension stone blocks depends on the proper selection of the structural and technological parameters of the machine, the diamond wire, and the conditions and methods of extraction of a specific type of rock, [1].

Cutting speed, energy consumption and wear rate of diamond beads are the most important factors for evaluating the efficiency of a diamond wire saw and they directly depend on the resistances during cutting. Part of these resistances depends on the properties of the rock mass, which cannot be directly influenced. Strength, hardness and abrasiveness are key engineering properties of rock that affect sawing performance and wear of beads. The energy consumption and service life of the diamond wire are directly related to the characteristics of the machine and the design of the diamond wire. The selection of design parameters such as the power of the drive motor, the diameter of the drive wheel, the grit size and concentration of diamonds and the diameter and number of beads can significantly influence the sawing efficiency. The operating parameters of the diamond wire saw, such as cutting speed, cutting angle, wire tension, machine position, cutting surface and cooling water flow also have a significant influence, [2].

Since the costs of sawing with diamond wire saw form a large part of the operating costs, it is important to know and choose the optimum machine working sizes in order to increase the efficiency and reduce the sawing costs. The main objective of this paper is, by analyzing previous studies, to determine the main factors that affect the power consumption and wear rate of diamond beads during the operation of a diamond wire saw, and to present guidelines for increasing the efficiency of operation of a diamond wire saw.

2. OPERATING AND DESIGN VALUES OF A DIAMOND WIRE SAW

A diamond wire saw consists of several main components, including a drive part, a control unit and a diamond wire as a cutting element (Figure 1). The drive part together with the flywheel is located in a housing that is mounted on metal wheels so that the machine can be moved along the rails during operation. The movement of the machine is accomplished by means of gears and a toothed rack between the rails, which also ensures the tension of the diamond wire. The power of the drive motor usually varies between 30 kW and 75 kW, and the choice of power depends on the cutting surface and sawing resistance. In addition to the drive wheel, there are also two guide pulleys on the frame that prevent the wire from falling out during operation and increase the closing angle of the diamond wire. By rotating the half-shaft, the drive wheel can be set in any position, allowing horizontal and vertical cuts to be sawn. There is also a protective rubber on the wheel that serves to protect the wheel and wire from wear and ensures the necessary coefficient of friction. The control unit is separated from the drive part and is usually located several meters to the side of the machine for worker protection.

When sawing the primary block with a diamond wire saw, it is necessary to have at least two free vertical surfaces on the bank. Before starting sawing, it is necessary to perform preparatory actions, which include drilling two mutually perpendicular horizontal and vertical holes around the surface that needs to be sawn, so that a diamond wire can be passed through them and closed in an infinite loop. The movement of the wire is achieved through a drive wheel driven by a flywheel connected to the drive motor, and the transfer of force from the wheel to the diamond wire is achieved by friction. During sawing, the machine moves away from the cutting surface along rails, constantly ensuring wire tension, and during sawing, it is necessary to ensure a constant flow of water. The tension of the wire is achieved by the machine feed motor, where the traction force must be adjusted to the sawing resistances. With modern saws, wire tension control and wire peripheral speed are automatically regulated depending on the sawing resistances.

Figure 1. Diamond wire saw and control unit

2.1 The diamond wire design

The diamond wire is the key cutting element of the diamond wire saw. Its design has a significant influence on sawing efficiency. It consists of a steel rope with diamond beads, protective steel rings, crimps, separating springs and male-female connectors placed on it (Figure 2).

Steel rope is an important part of the cutting tool because all other components are strung on it, so it is exceptionally important for the rope not to break. It must be corrosion resistant, flexible and have high strength. The diameter of the rope is usually about 5 mm, which allows it to easily pass through diamond beads that have the same inner diameter. The most commonly used rope of 61 wires is flexible enough and is less damaged when bending at the rigid part where the connector is located. Ropes with fewer wires proved to be too rigid, and those with more wires are too sensitive to the use of connectors with sharp sawing angles.

The most important part of the wire is the diamond beads, which play a key role in cutting, and influence the consumption and efficiency of the tool. Diamond beads can be cylindrical or conical in shape. An important part of the bead is the diamond layer, where there is diamond grit that can be bound in different ways, with different concentrations and particle sizes. The selection of these parameters usually depends on the type of rock being sawn. Sintered cylindrical diamond beads with a total length of 8.5 mm with outer diameter of 10 mm and inner diameter of 5 mm are used for limestone. The brand of diamonds is SDA type (synthetic) particle size 40/50 mesh with a diamond concentration of 35%, [3].

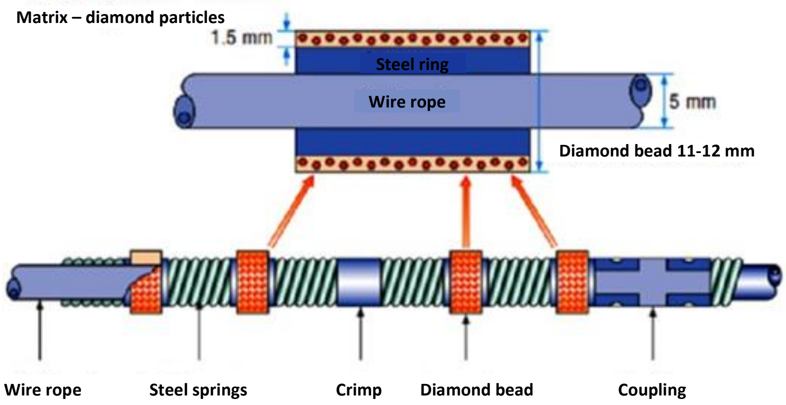

Figure 2. Diamond wire structure, [4]

3. SAWING EFFICIENCY OF A DIAMOND WIRE SAW

The sawing efficiency of a diamond wire saw is expressed as the rate of the sawn area per unit of time, usually in one hour. From Table 1, it is evident that the sawing efficiency is influenced by a large number of parameters, and most of these parameters are interrelated, which makes it difficult to precisely determine the effect of individual parameters on the sawing efficiency. Some of these parameters are uncontrolled and are related to the characteristics of the rock being sawn, such as strength, hardness, moisture content, degree of weathering, presence of fractures and mineral composition and texture of the rock.

There are also parameters that we can partially control, and they are related to operating values, machine characteristics and diamond wire design. These include motor power, linear wire speed, type and number of diamond beads per meter of wire, cutting area and shape, machine position and water consumption. According to research conducted by Almasi et al., all parameters affecting the sawing process are divided into two categories: controlled and uncontrolled, [2].

Table 1. Influence parameters when cutting with a diamond wire saw, [2]

Uncontrolled parameters	Controlled parameters	
Rock properties	**Design values**	**Operating values**
Physical properties	Power of drive motor	Machine operator skill
Porosity	Voltage	Applied sawing techniques
Particle size and shape	Drive wheel diameter	
Quartz content	Type of diamond beads	
Water absorption	Size, type and density of diamonds	
Degree of cementation	Number of beads per meter	
Mechanical properties	**Operating values**	
Strength	Linear wire speed	
Hardness	Feed force	
Abrasiveness	Wire entry angle	
Fragility	Wire length	
Elasticity	Type of cut	
Structural properties	Geometry of the cut	
Condition of discontinuities	Wire distance from the face	
Mineralogical composition	Orientation and amount of water	
Texture		

In softer rocks like travertine and marble, the efficiencies range from 5 m^2/h to 12 m^2/h. On the other hand, in limestone quarries, the efficiencies are somewhat smaller and usually range from 5 m^2/h to 7 m^2/h, [5].

3.1 The influence of rock properties on the sawing efficiency of a diamond wire saw

In most mining machines, regardless of the rock mass excavation mechanism, uniaxial compressive strength has a decisive influence on their efficiency and is an important factor in many rock mass classifications. In this regard, diamond wire saws are not an exception, which is corroborated by previous studies, [6], [7], [8]. The results of the said studies show that the cutting speed and sawing efficiency decrease with increasing strength of the rock being sawn. Although to a lesser extent, hardness, abrasiveness, brittleness also has a significant influence on sawing efficiency, [6], [9], [10].

When sawing marble with pronounced anisotropy, the highest efficiency is achieved when sawing the stone parallel to the stratification, and the lowest when sawing perpendicular to the stratification, [7]. The texture coefficient can also have a decisive influence on the sawing efficiency. Tests have shown that in the case of marble and limestone, increasing the texture coefficient reduces the sawing efficiency, [11], [12]. Quartz content and modulus of elasticity can also have a significant effect on sawing efficiency, [8].

Khoshouei et al. 2020 measured sawing energy on a laboratory diamond wire saw. Tests were carried out on samples of diorite, syenite, gabbro, granite and andesite (Figure 3), [13]. The results showed that the density, abrasiveness and p-wave velocity have the highest correlation with specific energy. A model for estimating the specific cutting energy with an accuracy of 85.8% was developed using multiple regression analysis.

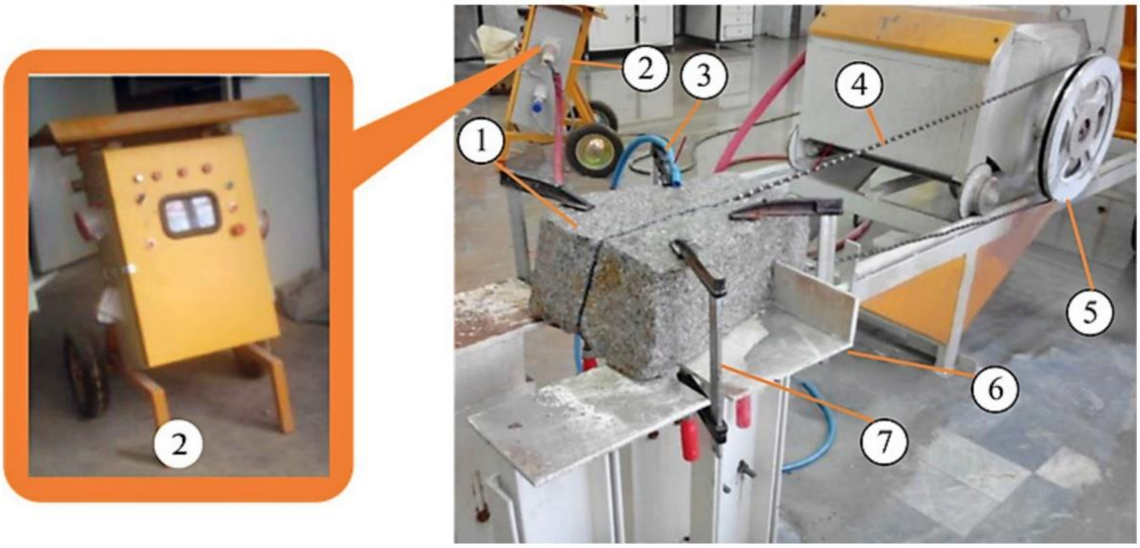

Figure 3. Laboratory diamond wire saw: 1 - Rock sample; 2 - Energy consumption measurement unit; 3 – Inflow of cooling water; 4 - Diamond wire; 5 - Drive wheel; 6 - Platform; 7 - Clamps for samples, [13]

3.2 The influence of design and operating values of a diamond wire saw on sawing efficiency

The selection of design and operating values of the diamond wire saw has a decisive influence on the cutting efficiency. The sawing efficiency will depend on the resistances due to the movement of the diamond wire during sawing. Sawing resistances depend on the properties of the rock being sawn, but also on operating parameters such as cutting speed, cutting angle, wire tension, machine position, cutting surface and shape, and cooling water flow. It is precisely for this reason that it is important to apply operating parameters for which the wire will have the best results.

One of the parameters is the shape of the sawing trajectory, which is determined by the dimensions of the cut and the position of the diamond wire in relation to the sawing surface. Dunda and Štambuk, 1994 analyzed the influence of the position of the saw on the sawing efficiency of a diamond wire saw at the Zečevo quarry on the island of Brač, [1]. Their research established that the lateral position of the saw (Figure 4.b) relative to the length of the horizontal cut results in a 14.6% higher average sawing efficiency than the central position of the saw (Figure 4.a). In addition, by placing the saw laterally, it is possible to saw 12.37 m^2 more with one meter of wire length, and the sawn area is 29.7% larger than with the central position with the same consumption of diamond wire.

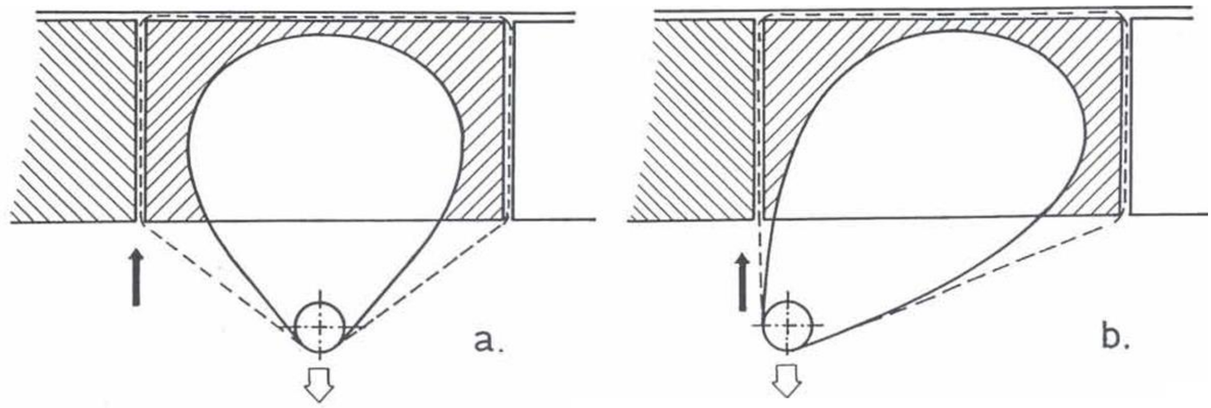

Figure 4. Possible positions for a horizontal cut, a) central position, b) lateral position of the saw, [1]

When making a vertical cut, the position of the saw cannot be significantly changed, therefore the shape of the trajectory depends primarily on the dimensions of the cut. The main difference in the shape of the trajectory when making a vertical cut comes from the way or position of the saw when making the cut, which can be by height or by depth. For the method of cutting by height, the saw is located on the bench on which the block is lowered, while for cutting by depth, the saw is placed on the bench being sawn. A cut by depth is performed using an auxiliary wheel, which causes additional resistance at the exit from the cut. In practice, it has been shown that better sawing results are achieved when the saw is located on the bench on which the block is lowered. However, this position is not always possible to realize due to space limitations or other organizational or operational reasons, [1].

Khademian et al. 2015 analyzed the optimal distance between the saw and the face of the bench when sawing vertical cuts in the extraction of travertine, [14]. The tests were carried out on benches with a height of 7 m to 12 m at distances between the saw and the bench face ranging from 1.5 m to 5.5 m (Figure 5.a). The cut widths ranged from 5 to 12 m. They established that with an increase in the height of the face, the optimal distance between the saw and the working face also increases and that the highest sawing efficiency is achieved with the largest bench width, regardless of its height. It is evident in (Figure 5.b) that the optimal distance between the saw and the face of the bench with a height of 7 m is 3 m, regardless of the width of the cut. For benches with a height of 10 m and 12 m, the optimal distance between the saw and the face is 3.5 m and 4.5 m.

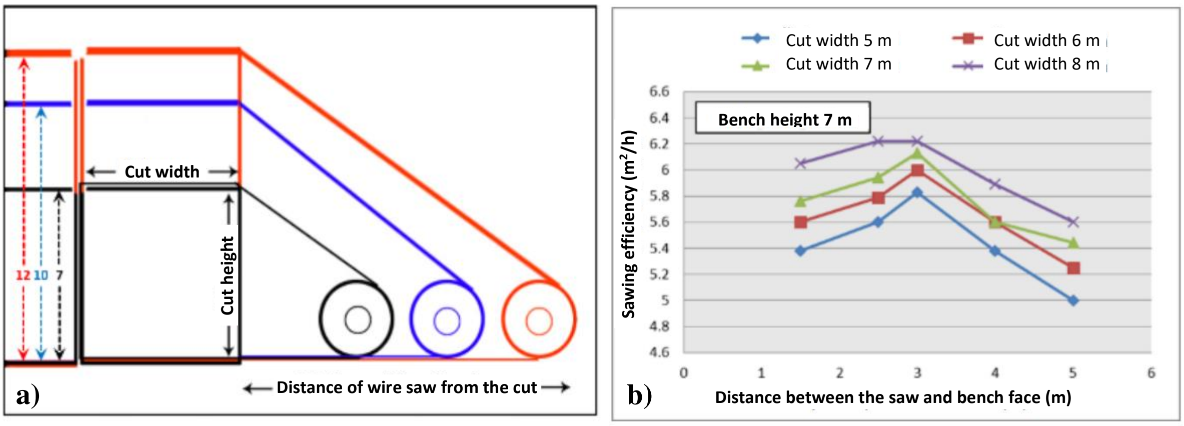

Figure 5. a) Geometry of the vertical cut depending on the position of the diamond wire saw b) Sawing efficiency for a bench height of 7 m, [14]

In order for sawing to be possible, the traction force on the rim of the drive wheel of the diamond wire saw must overcome all the resistances that occur during movement of the diamond wire. An increase in the sawing area increases the length of the diamond wire, which ultimately results in higher resistances and higher traction force. It is precisely for this reason that it is necessary to adjust the power of the drive motor to the sawing resistances, thus ensuring sufficient tension of the wire. Almasi et al. 2015 determined the optimal tension of the cutting wire depending on the cutting surface when sawing travertine blocks, [2]. The tests were conducted on areas of 50 to 100 m^2, changing the value of traction force, with the current of the feed motor ranging from 45 to 65 amperes.

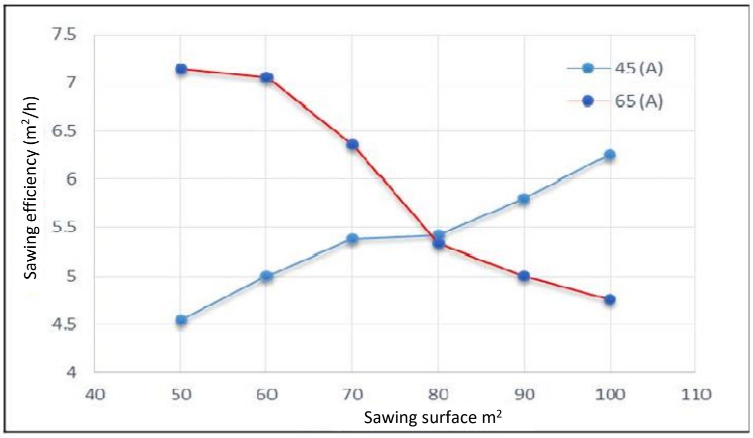

Figure 6. Influence of sawing surface and traction force on sawing efficiency, [2]

In order to achieve optimal efficiency, when sawing cuts of small areas, smaller than 60 m^2, it is purposeful to increase the traction force if the power and structure of the saw allow it. When sawing cuts of larger areas, it is more appropriate to reduce the tension of the wire. With a cut surface of 80 m^2, the sawing efficiency is the same for the maximum and minimum traction force, but for safety reasons it is better to work with a smaller feed (Figure 6).

Rasti et al. 2021 measured the performance and wear rate of diamond wire in limestone, travertine and marble quarries, [6]. Analyzing the measured data, the authors found that by increasing the cutting angle in relation to the bench face, the efficiency decreases while the wear rate of diamond beads increases (Figure 7.a). From the above, it follows that greater sawing efficiency is achieved when sawing vertical cuts than when sawing horizontal cuts. The authors also established that increasing the diameter of the drive wheel increases the cutting efficiency, which is a consequence of increasing speed (Figure 7.b).

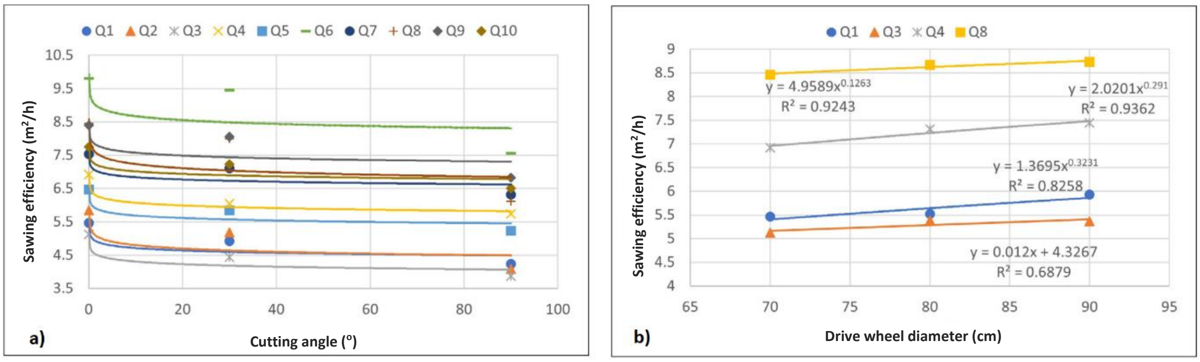

Figure 7 a) Influence of cutting angle on sawing efficiency b) Influence of drive wheel diameter on sawing efficiency, [6]

Increasing the diameter of the drive wheel also has additional benefits such as reducing the unevenness of the diamond wire movement, thus reducing speed and acceleration fluctuations. Namely, the linear speed of the wire is not continuous but moves at intervals. The reason for this is that the wire is not in constant contact with the drive wheel, but the transfer is achieved by contact or friction between the beads and the drive wheel. With a constant speed of the wire and increase in the radius of the drive wheel by n times, the maximum acceleration will be reduced by nx2 times, and thus the dynamic stresses caused by the uneven transfer of motion from the drive wheel to the diamond wire will also be reduced, [15].

4. WEAR OF DIAMOND BEADS

One of the key factors affecting the cost-effectiveness of diamond wire cutting is the wear of the diamond beads. A reduction in wear of diamond beads will also reduce the cost of diamond wire cutting. A large number of parameters can affect the wear of diamond beads, among which the texture and engineering properties of the rock and the operating size of the diamond wire saw are particularly emphasized. Therefore, when sawing stone, it is very important to apply operating parameters for which the wire will achieve the best results. During operation of the saw, it is necessary to continuously monitor the wear of the beads to ensure efficient sawing. Worn wire will result in poor efficiency and increased power consumption.

The wear of diamond beads can be determined by measuring the mass of the bead or by measuring the volume of the bead before and after sawing. By measuring the mass of beads, it is possible to determine the specific wear of beads per meter of wire mg/m´ or per unit area of the sawn cut mg/m^2. In order to determine the specific wear of wire expressed in meters of worn wire per m^2 of sawn surface, it is necessary to divide the specific wear expressed in mg/m^2 by the total mass of the diamond layer per m´ of wire. The total mass of the diamond layer per m´ of wire is determined by multiplying the mass of the diamond layer of one bead by the number of beads per m´ of wire, [1].

Several authors determined the wear of beads in laboratory conditions by measuring the change in bead volume due to cutting, [10], [11], [16], [17]. Micrometers or microscopes with the use of computer programs for image processing are used to determine the change in bead volume due to cutting (Figure 8).

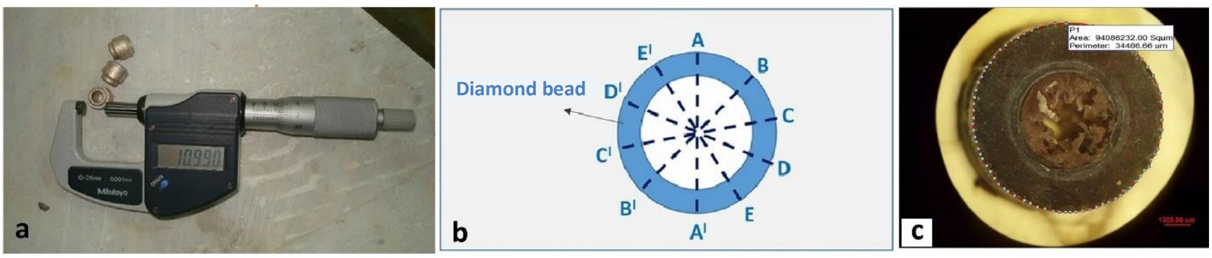

Figure 8. a) micrometer b) bead diameter measurement position c) microscopic image of a bead, [17], [18]

The specific wear of beads by measuring the change in volume and cut area is calculated according to the following equation:

$$UW = \frac{d_0 - d_1}{A} \tag{1}$$

where: UW is the unit wear of diamond bead (μm/m^2), d_0 is the diameter of a new diamond bead before cutting (μm), d_1 is the diameter of the worn diamond bead after cutting (μm), and A (m^2) is the area of the cut sawn during the test.

In a travertine quarry in Iran, a study has determined that the optimal sawing efficiency with a diamond wire saw is undoubtedly influenced by the number of beads per meter of wire length, where the highest efficiency is achieved with 31 beads per meter of length, at the middle third of the bead lifetime (Figure 9), [19].

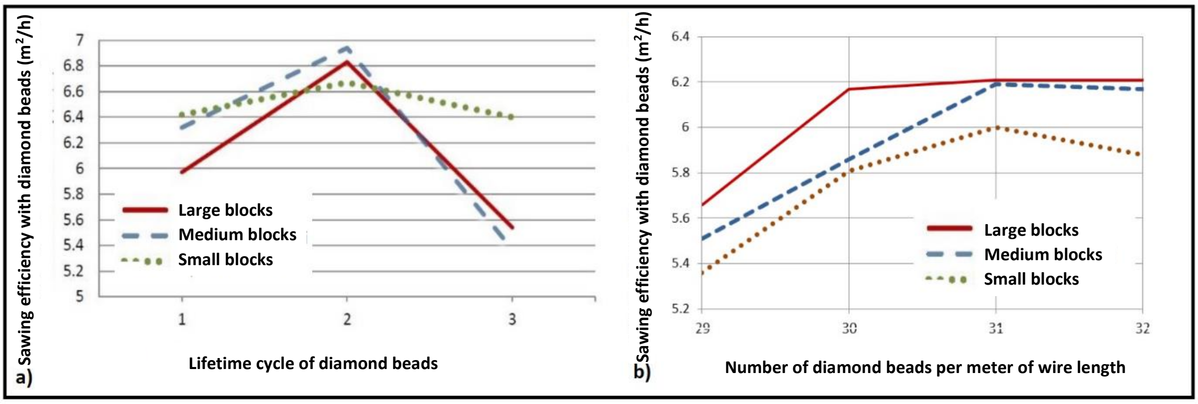

Figure 9 a) the influence of the life cycle of diamond beads on the sawing efficiency b) the influence of the number of beads on the sawing efficiency, [19]

According to the tests carried out by Özçelik 2003 at an andesite quarry in Turkey, the wear of diamond beads is mostly influenced by the rock parameters (elasticity and specific density), and the operating values of the machine (cutting time and energy and water consumption), [20]. Yilmazkaya and Özcelik 2016 established a significant dependence of the degree of wear of diamond beads and uniaxial compressive strength and a slightly smaller dependence with tensile and impact strength, [21]. They also found that by increasing the abrasiveness value determined according to Böhme, the wear of the beads decreases as well as by increasing the open porosity. Ozcelik et al. established a significant dependence of diamond bead wear on the limestone texture coefficient. As the values of the limestone texture coefficient increase, the specific wear of diamond beads increases and the cutting efficiency decreases. In addition, they concluded that in the case of limestone and marble, increasing the mineral grain reduces the wear of diamond beads, [11]. Rajpurohit et al. analyzed the wear of diamond beads when sawing granite. Based on the results, they proposed a multiple regression model for the assessment of bead wear, which includes four rock properties: point strength index, Cerchar abrasivity index, uniaxial compressive strength and modulus of elasticity, [10].

Rasti et al. 2021, [6] found that when cutting marble, the wear rate of beads increases with increasing uniaxial compressive strength and hardness determined by the Schmidt hammer, and decreases with increasing abrasion. In addition, they found that an increase in the cutting angle increases the wear of diamond wire, that is, the wear of beads is higher when sawing a horizontal cut than with a vertical cut. An increase in the peripheral speed and traction force increases the cutting efficiency, but at the same time the wear of beads increases, [9], [16]. The authors also concluded that an increase in cohesion results in an increase in bead wear and a decrease in cutting efficiency. Konstanty 2021 observed that excessive traction force when sawing granite results in conical wear of the beads (Figure 10), [22].

Figure 10. Wear of diamond beads due to excessive traction force, [22]

5. CONCLUSION

Based on previous studies, the paper analyzes the efficiency of diamond wire saws and the consumption of energy and wear rate of diamond wire when sawing stone. With softer rocks in travertine and marble quarries, efficiencies of 5 m^2/h to 12 m^2/h are achieved, while in limestone quarries the efficiencies are somewhat smaller and range from 5 m^2/h to 7 m^2/h. The average sawing efficiencies in granite range from 2 m^2/h to 5 m^2/h, although larger efficiencies have been registered in some quarries.

The sawing efficiency as well as the consumption of energy and wear rate of diamond beads are influenced by numerous parameters. It is not possible to influence some of these parameters, given that they are defined by the working environment or the properties of the rock being sawn. The uniaxial compressive strength of the rock has a decisive influence on the sawing efficiency and wear rate of beads. Hardness, abrasiveness, brittleness, texture coefficient, quartz content and mineral grain size have a slightly smaller but still significant influence on the sawing efficiency.

The operating and design values of the diamond wire saw are among the parameters that can be partially controlled and have a significant influence on stone sawing. In order to achieve optimal sawing efficiencies, it is important to choose the operating parameters correctly, where attention should be paid to the following guidelines:

- The optimal sawing efficiency with a diamond wire saw depends on the number of beads per meter of wire length, and the highest registered efficiency was achieved in travertine with 31 beads per meter of wire length, and so at the middle third of the wire lifetime. The most acceptable way of forming the wire with installation of a crimp after every 5 diamond beads with 30 beads per meter of wire length has been established in most Croatian quarries.
- When making a depth vertical cut, increasing the height of the face increases the optimal distance between the saw and the working face. When sawing travertine at

bench heights of 7, 10 and 12 meters, the optimal distance between the saw and the face is 3, 3.5 and 4.5 m.

- When making a horizontal cut, the lateral position has an advantage over the central position in terms of efficiency and diamond wire wear.
- The sawing efficiency increases with increasing feed force and increasing diameter of the drive wheel, and decreases with increasing sawing angle. In addition, increasing the diameter of the drive wheel decreases the dynamic stresses caused by the uneven transfer of motion from the drive wheel to the diamond wire.
- When sawing a cut area of less than 60 m^2, it is purposeful to increase the traction force if the power and structure of the saw allow it. When sawing cuts of larger areas, it is more appropriate to reduce the tension of the wire in order to increase the sawing efficiency. An increase in the traction force results in greater wear of the beads, and excessive traction force when sawing granite results in conical wear of the beads.

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