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RESEARCH ARTICLE

A NEW PERSPECTIVE ON REDUCING ENERGY CONSUMPTION IN GRANITE CUTTING WITH A MULTI-BLADE BLOCK CUTTER: THE CASE OF AN INDUSTRIAL APPLICATION

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ABSTRACT

In recent years, the use of natural stone, especially in the construction sector, has increased as a result of rapid economic development. One of the most important cost parameters in natural stone cutting processes is energy costs. Generally, cut granites with block cutters differ from other rocks in terms of both the cutting machines used and the energy consumed. Increases in energy prices and emission reduction requirements require cutting processes to work most efficiently. This article describes the energy consumption process in a stone processing plant, and makes recommendations to decision-makers for the more efficient use of energy. A total of 456 real cutting tests were conducted at three different cutting depths and at three different feed rates using a multi-blade block cutter with 10 saw blades at a plant with a monthly production capacity of over 4000 square meters. Real time energy consumption values were recorded with the help of a power analyzer installed on the control panel of the block cutter. The obtained data were used to calculate specific cutting energy values, and the energy consumed throughout the entire process was analyzed. The energy consumption values as the saw blade moves back and forth were examined in eight different regions, starting with the first phase in which the saw blade approaches the granite block. From the obtained power consumption values and calculated specific cutting energy values, an approach has been introduced in terms of cutting efficiency to the specific cutting energy values and energy consumption characteristics in rock cutting processes using circular saw blade.

Keywords: Rock cutting, Granite, Multi-blade block cutter, Energy efficiency, Specific cutting energy

1. INTRODUCTION

With its timeless strength, color options and aesthetic qualities, natural stone has long been a popular material in the construction sector, and has seen a considerable increase in use especially in recent years. Granite is commonly used in landscape architecture for exterior spaces, art installations and as a building material, due to its hardness, its resistance to environmental effects and its multi-color appearance.

Natural stone processing refers to all of the processes, from the extraction of the blocks from natural stone quarries to the process to turn them into end-products. The granite production chain is high energy and water intensive, and is characterized also by low resource efficiency [1].

In general terms, the amount of energy consumed for the processing of natural stone depends on the petrographic properties of the stone in question, although any evaluation of the energy efficiency used for the processing of natural stone requires a holistic perspective that takes into account all stages of production, from extraction to disposal [2].

Granite is usually cut using a block cutter, and is different from other rock materials both in terms of the cutting machines used and the energy consumed. Increases in energy prices and the difficulties involved in cutting hard stone necessitates the development of the most efficient models based on cutting tests. All of the steps in a natural stone cutting process involve electricity, and so energy is one of the most significant cost items in stone cutting processes using circular saw blades [3]. As a result of

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technological advances and increased production, energy costs have also significantly increased in recent years. Moreover, energy consumption has increased in parallel with the increased demand for natural stone, which necessitates energy savings.

The natural stone cutting sector consumes large amounts of electricity, and this study uses data garnered during cutting tests to break down the energy consumption characteristics of a granite cutting process, analysing the entire operation involved in processing this hard and difficult to cut stone.

This article is addressed to engineers, production managers and stone producers with a view to reducing energy consumption. The applied methodology involves a detailed examination of the energy consumed during the cutting process, defining each stage in the process, and an evaluation of how to reduce energy consumption.

In one of the earlier studies of natural stone cutting, Tönshoff and Warnecke [4] examined the relationships between machine tool, work piece and cutting parameters, and proposed a chip removal model for different cutting mechanisms, taking the diamond distribution across the surface of the saw blade into account. In another early study, Jennings and Wright [5] identified the factors affecting saw blade performance. In addition to the matrix and diamonds in the segment of saw blade, they found that the sawing mode, peripheral blade speed, sawing rate, machine condition, and operator's skill were the main criteria affecting saw blade performance

Almost all of the early studies examine the wear characteristics that lead to high energy consumption, rather than to energy consumption itself, and argue that the wear process must be understood if the optimum process parameters and tool composition are to be established. [6,7].

In a study focusing on the theoretical analysis of the cutting process, Konstanty [8] claimed that the performance and lifespan of saw blades are affected by many factors, besides the diamond and the matrix selected, such as operator skill and cooling efficiency. The study examined the kinematics of both the up- and down-cutting modes, and defined the forces acting on the saw blade in each cutting mode. Brook [9] carried out studies of both circular saw cutting and frame sawing in a laboratory-scale study involving 10 different sawing tests, and concluded that radical new approaches would not be able to resolve the problems of rock sawing, suggesting that a large number of studies would be needed to pave the way for future work.

Tönshoff et al. [10] examined the principles of cutting processes and their relationship with tool and process design, and argued that the optimum process parameters and processing conditions could be established through studies of only cutting principles and wear performance. While cutting processes are certainly affected by these factors, in contemporary industrial settings, many other factors are known also to play a role. A study by Konstanty [11] examining the saw blades used not only in the natural stone sector, but also in construction, road repair and ceramics, made recommendations regarding the selection of the metallic matrix for the design and production of diamond impregnated segments, and the use of the right diamond abrasives for each task.

Emphasizing that wear and energy consumption are the leading parameters affecting production costs in natural stone cutting, Buyuksagis [12] examined cutability of granite, carrying out tests on granite involving both up and down cutting modes. In this laboratory-scale study, a blade with a diameter of 400 mm was used, set to a cutting depth (d) of 20 mm and a feed rate (V_f) of 0.45 m/min. The specific energy values and specific wear values obtained from the study were associated with rock properties. The study concluded that bending strength was the single most important determinant of specific cutting energy, while the plagioclase content of the rock was found to explain the specific cutting energy.

Yurdakul [13] examined the effects of some cutting parameters on consumed power. The tests were conducted in an industrial setting using a single-blade block cutter with a diameter of 1200 mm, at various feed rates and cutting depths (d). This study – which is the only industrial-scale study in literature – examined the effects of d and V_f on consumed power based on cutting tests conducted with Balmoral red granite with single blade block cutter.

More recent studies have proposed models for the estimation of natural stone cutability and production amounts. In a study conducted involving artificial neural networks, Tumac [14] attempted to estimate slab production rates on the basis of Brazilian tensile strength, Cerchar abrasivity index, uniaxial compressive strength, porosity and density values, and found that artificial neural networks could be used to estimate slab production with five inputs.

In recent years, the concept of sustainable production has gained prominence as a result of the increased environmental awareness, the greater preference for green buildings and the increasing energy costs. Bai et al. [15] conducted a study into the selection of sustainable technologies for the cutting of granite blocks into slabs. Based on the multiple-attribute decision-making techniques that they developed, they created a new approach to technology selection process that was based on environmental, economic and technical indicators.

Aryafar and Mikaeil [16] studied energy consumption in natural stone cutting on the basis of ampere consumption, and underlined that reducing energy consumption would increase production efficiency, developing a model for the estimation of current consumption using artificial neural networks involving laboratory-scale tests with carbonate rock samples under different conditions. They found that the models that had machine and work piece characteristics as inputs were successful in estimating current consumption values.

Noting that power consumption during cutting is important for optimization, monitoring and control, Huang et al. [17] proposed a model for the estimation of sawing power based on tangential force distribution, and reported that their model could lower power consumption by 28%. Tumac and Shaterpour-Mamaghani [18] developed simple multiple linear and non-linear regression models to estimate slab production based on the physico-mechanical properties of rocks. They reported that the best model that they developed was a multiple non-linear model that was a function of the Schmidt hardness value and the Shore hardness value of sedimentary natural stones.

Almost all studies in literature have sought to understand the relationship between wear and the physico-mechanical properties of rocks. The present study, on the other hand, aims to underline how the process works in terms of energy consumption, how the entire cutting process should be examined, and how efficiency can be established on the basis of energy consumption and real cutting processes with a view to achieving clean and efficient production.

As the above review of literature shows, we encountered no studies investigating the energy changes, energy consumption or specific cutting energy involved in the up-cutting and down-cutting of granite in an industrial setting.

On the basis of these observations, the present study examines energy consumption values in granite sawing processes in the up- and down-cutting modes using a multi-blade block cutter under different sawing conditions. The cutting characteristic was analyzed separately for all stages of the cutting process, from the first movement of the saw blades until the completion of the cutting, and a new perspective was developed regarding energy consumption values in terms of cutting efficiency. In granite cutting processes involving shallow cuts, the industrial cutting conditions are quite different to laboratory conditions, in that the cutting is gradual, and the saw blades keep cutting as they move back and forth.

2. TEST PROCEDURES

2.1. Rock Properties

In natural stone cutting processes, the physical and mechanical properties of the material to be cut must be known in order to determine the forces to which the saw blade will be subjected and the corresponding energy consumption values, which the machine operator will use to decide upon the optimum V_f and d values. Moreover, saw blade manufacturers develop saw blade with characteristics suitable for the physico-mechanical properties of specific rocks. All data collected in this study were obtained in real time from a granite cutting exercise involving granite with the commercial name "Rosalin Granite" (with the petrographic name alkali feldspar granite) in sizes varying between 6 and 8 m^3. The granite material has quartz, alkali feldspar, plagioclase, biotite and muscovite in its mineralogical composition, and has a hypidiomorphic granular texture [19] (Figure 1). Knowledge of these properties can aid in the evaluation of the energy consumption characteristic of similar rocks.

Figure 1. Macro and thin section views of the rock subjected to cutting tests.

Cutting costs, which are affected by the performance of the saw blade, are dependent, to a large extent, on the cutting speed, and deciding on an appropriate cutting speed requires identifying such factors as the parameters of the cutting operation and the properties of the rock to be cut [20]. Table 1 presents the results of the physico-chemical tests conducted to identify the rock cut in the study.

Table 1. Properties of the rock subjected to cutting tests.

Property	Test Standard	Unit	Value	Standard Deviation
Uniaxial compressive strength	EN 1926	MPa	174	-
Flexural strength	EN 12372	MPa	9.33	1.1
Water absorption at atmospheric pressure	EN 13755	%	0.5	-
Water absorption coefficient by capillarity	EN 1925	$g/m^2s^{0.5}$	59.22	-
Apparent density	EN 1936	kg/m^3	2590	10%
Frost resistance	EN12371	% [1]	9.44	-
Abrasion resistance	EN 14157	mm	12.25	0.48
Breaking load at dowel hole	EN 13364	N	1500	323.86

[1] Change in mean flexural strength after 48 cycles.

Moreover, standard samples were taken from the cut blocks, and X-Ray Fluorescence (XRF) was used for the chemical analysis of the samples, the results of which are presented in Table 2. Hauseberger [1] argues that if we can understand the mineralogical structure of a rock, we can also understand its cutability. The rock subjected to cutting tests in the present study is relatively difficult to cut due to its quartz, alkali feldspar and plagioclase content.

Table 2. Chemical composition of Rosalin granite samples (%) determined by XRF.

	%
SiO_2	81.12
Al_2O_3	14.79
K_2O	3.18
CaO	0.30
FeO	0.26
Fe_2O_3	0.19
TiO_2	0.07
MnO	0.03
BA	0.01
Rb	0.02
Zr	0.01
Th	0.01

2.2. Cutting Machine and Tool Properties

All of the cutting tests were conducted with a multi-blade block cutter with 10 saw blades, four columns and a 37 kW motor that turns the blades (Figure 2). The gradual cutting of the block is achieved through the machine's forward and backward cutting motion. The machine is controlled from a computer-assisted control panel that is used to adjust such cutting parameters as feed rate, cutting depth and cooling fluid flow. The saw blades used in the study had diameters of 1100 mm, and each saw blade comprised 74 conical sandwich-type segments. The rotational speed of the saw was 375 RPM (revolutions per minute). In multi-blade block cutters in particular, lower rotational saw speeds are used due to the excessive forces applied to the mill carrying the blades. The flange diameter of the block cutter was 250 mm, and each segment was 6.9–7.6 mm wide, 10.4 mm high and 24 mm long. The segments had an initial height of 12 mm, although the cutting tests were conducted when the segments were 10.4 mm high, as the machine is operated at a lower than standard feed rate when the segments are new.

Figure 2. Multi-blade block cutter with 10 saw blades used in the study.

As the diamond particles in the segments become visible, that is to say, as the segments become sharper, the saw blade is run at the same speed for the rest of its lifespan. During the cutting tests conducted for the study, the segments were operated at the optimum cutting speed. The saw blade bodies were made of 75 Cr1 steel, had a Rockwell hardness value of 40–44, a diameter of 1084 mm and a thickness of 5.5 mm. The water channels on the saw blades were 20 mm high and 22 mm wide.

Saw blade wear values were not taken into consideration in the present study. The plant in which the cutting tests were carried out had been cutting a minimum of 2000 m² of rock a month since 2006, and only cuts Rosalin granite. Accordingly, the plant operators were assumed to have achieved maximum saw blade performance due to their long years of experience. It was believed that the plant would have achieved the optimum saw blade body and segment set-up as a result of many trials over the years, and this assumption was confirmed through observation.

2.3. Obtaining Electricity Data for the Cuts

In natural stone cutting, standard power measurement methods are commonly used for the evaluation of the cutting performance of saw blades. In cutting processes, there is an association between cutting forces and power consumption, but as it is much easier to measure the power consumed than to measure the forces exerted, estimations for cutting optimization tend to be based on the power consumption values [2]. The present study measured real-time energy consumption values under different cutting conditions. A mobile power analyzer was used to measure power consumption in real time during cutting. Connection elements were used to connect the power analyzer to the power line at the main control panel of the machine, providing energy to the main motor. The power values were recorded in real time separately for each cutting condition, and transferred to a computer via a software program.

2.4. Cutting Tests, Power Consumption and Specific Cutting Energy

More than 400 cutting tests were conducted at three different V_f (5, 7, 9 m/min) and three d values (10, 14, 18 mm) for each V_f. The cutting conditions are detailed in Table 3.

Table 3. Cutting conditions under which the cutting data were obtained

V_f (m/min)		d (mm)	
Forward	Backward	Forward	Backward
5	5	10	10
		14	14
		18	18
7	7	10	10
		14	14
		18	18
9	9	10	10
		14	14
		18	18

After recording the real-time energy consumption values, the specific cutting energy values were calculated for each cutting condition.

Data were recorded for a minimum of 30 cycles for each cutting condition, and the mean values were calculated. Repeated measurements were taken under each cutting condition to reduce the effects of the variation of rock properties.

As industrial granite cutting processes, cutting is made in both feed directions (forward and backward) without changing the saw blade rotation direction, which is different to single-blade cutting operations. In the present study, the saw blades used the up-cutting mode during forward movement, and the down-cutting mode upon their return.

Saw rotation speed is one of the most important factors to be controlled in cutting processes. In the present study, the rotational speed of the saw was measured without contact using an optical tachometer. Prior to recording the data, as the saw blade was submerged entirely within the block, and the revolutions per minute (RPM) value was recorded using the tachometer. The measured RPM value was 375, and so the peripheral speed under these cutting conditions was calculated to be (V_p) 21.60 m/s. In some studies in literature, a peripheral speed of around 25 m/s is recommended when cutting granite containing quartz, which can be difficult to cut [2,3].

The variable characterizing energy use per produced product is often referred to in literature as specific cutting energy (SE_{Cut}) values [4–6]. SE_{Cut} can be calculated using Equation 1 either on the basis of cutting forces or on power consumption values [5,7,8].

$$SE_{Cut} = \frac{P_C t}{Q_w . t} = \frac{F_T . V_P}{d W_C V_f} \ (J/mm^3) \quad (1)$$

where SE_{Cut}: Specific cutting energy, P_C: Consumed power for cutting, t: Cutting time, Q_W: Cutting volume (mm^3/s), F_T: Tangential force (N), V_P: Peripheral speed (mm/s), d: Cutting depth (mm), W_C: Width of cutting channel (mm), V_f: Feed rate (mm/s).

3. RESULTS AND DISCUSSION

In general terms, the environmental and economic performance of granite processing plants are known to be affected significantly by the adopted cutting technology [15].

Studies in literature of natural stone cutting include studies by various researchers on saw blade wear characteristics, saw blade performance and specific cutting energy, while there is a lack of studies examining the behavior of saw blades as they cut the rock, and the associated energy consumption. The present study evaluates saw blade behavior in terms of energy consumption, and makes recommendations for the improvement of cutting performance

3.1. Energy Consumption in Cutting Tests

Data were obtained for more than 400 cutting cycles in this study, and the average of a minimum of 20 cutting cycles for each cutting condition was calculated to reduce the effects on energy consumption of the macro and micro physico-mechanical properties of the rock in different parts of the block. The energy consumption values for each cutting condition are presented in Table 4.

Table 4. Variation in consumed power (W) by V_f and d (400 cycle).

	Depth of cut, d (mm)					
	10		14		18	
Feed rate, V_f (m/min)	Up	Down	Up	Down	Up	Down
5	11287	11488	13743	13702	15704	15936
7	12891	13368	15805	15918	18477	18495
9	14956	15065	17765	17978	20837	21302

The energy consumption values for each cut during the cutting of the granite block were recorded, beginning with the up-cutting mode, and following the measurement of the down-cutting mode, an entire cycle was examined. Figure 3 shows the variation in energy consumption during the forward and backward movements of the saw blade, presenting a sample energy consumption-time graph for a cut with a depth of 18 mm and feed rate of 7 m/s. All cuts were carried out under similar conditions, with only the duration and energy consumption values being changed. To avoid complicating the picture with multiple graphs, the overall results were discussed based on a single cut that summarized all cuts.

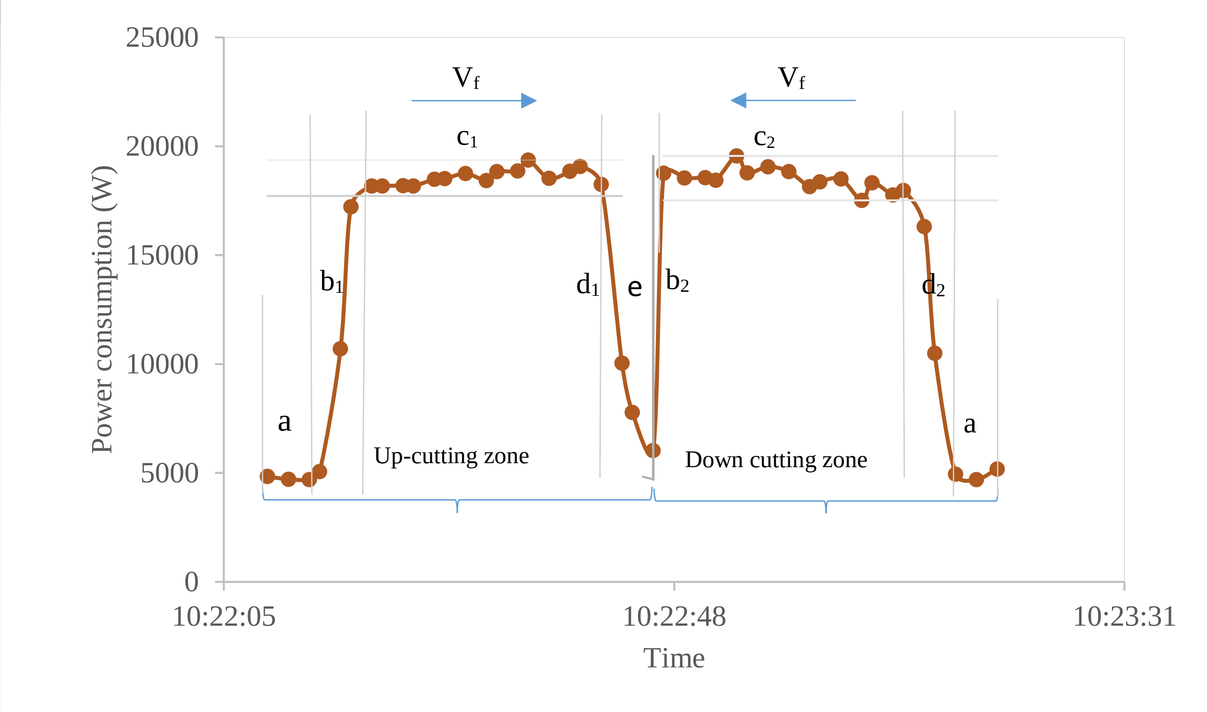


Figure 3. Overall saw blade energy consumption curve during the forward and backward movement of a complete cutting cycle.

In cutting processes that combine up-cutting and down-cutting, in which the saw blade cuts during both the forward and backward movements, the entire machine-tool energy consumption can be divided into 8 zones (Figure 3.: a, b_1, c_1, d_1, e, b_2, c_2, d_2).

In all natural stone cutting operations carried out with block cutters, the circular saw blade moves toward the rock from a start point, and following the cut, returns to the same point. The point at which the cutting operation begins and to where the saw blade returns are set by the operator. The region between the start point and the first point of contact between the machine and the rock is labelled "zone a" in Figure 3. In zone a, the machine is not cutting, and the energy it consumes is equal to the energy the motor consumes when idle. In granite cutting operations carried out with a machine that cuts both in the forward and backward phases, there is no cutting in zone e, either, where the machine again consumes energy equal to the power consumption of the motor when idle. Zone e is the region in which the saw blades have completed the cutting operation and are returning to the start point after reaching the switch point set by the operator.

In these zones (a and e), the machine runs without cutting. In the present study, the time the machine spent in each of zones a and e was found to be around 10 seconds. In blocks with a cutting height of 2 meters, given that the saw blade cuts a total depth of 28 mm during its forward and backward movement, an average of 72 cycles would be required to cut the entire height of the block, and the 20-second loss in each cycle means that the machine would be idling for around 24 minutes (20 seconds x 72 cycles). In studies examining cutting efficiency and cutting performance, if the SE_{Cut} is evaluated solely on the basis of the actual cutting moments when the saw blade is in contact with the stone, the complete picture of the entire cutting cycle would not be recorded, as there are times when the machine is running idle and not cutting. In this case, the exclusive reliance on specific cutting energy would not be a good indicator of cutting efficiency, as a significant amount of energy is consumed in zones where no cutting is taking place. It is recommended that all natural stone cutting plants take this point into consideration.

The time from the moment the saw blades first come into contact with the rock until the moment when all segments are engaged in cutting is shown as zone b in Figure 3. The blades work in the up-cutting mode in zone b_1, and in the down-cutting mode in zone b_2. The saw blades are loaded with sudden cutting forces, and energy consumption values rapidly increase. In this zone, due to the sudden cutting forces acting upon the saw blades, cutting should be slower to avoid breaking the diamond pieces, although no contemporary block cutting machines used by the sector take this into consideration. The saw blades move at a constant speed throughout the entire cutting process, as block cutters do not have the necessary mechanism to increase or decrease speed depending on the cutting zone. Accordingly, in the zones where the saw blade enters and exits the block (Figure 3; zones b, e, and d), the saw blade moves faster than it should, leading to the early breakage of the diamond pieces, resulting in relatively inefficient cutting. A block cutter with speed control can achieve significant energy savings by keeping these zones under control.

Zones c_1 and c_2, where all segments are engaged in cutting across the cutting depth, should be evaluated separately.

In the up-cutting mode, from the moment the saw blades first come into contact with the rock until the moment when the saw blades start exiting the rock, there is a relative increase in consumed energy (Figure 3, zone c_1). In other words, in zone c_1 in Figure 3, from the moment all segments engaged in cutting first come into contact with the rock until the moment the segments start exiting the rock, energy consumption tends to increase. In the up-cutting mode, this is true for all cutting conditions, which can be explained with cutting kinematics. In the up-cutting mode, the diamond pieces move upward from the minimum to maximum thickness to achieve the desired cutting depth. This is explained by Konstanty [3] in their study of cutting forces in different cutting modes. In the up-cutting mode, the diamond pieces, and thus the saw blade, come into contact with the rock at the minimum cutting depth, and moving upwards in the vertical plane, reach the maximum penetration rate.

In the down-cutting mode (Figure 3 zone c_2), on the other hand, unlike in the up-cutting mode, the saw blade works to complete the cutting depth from the moment of first contact with the rock onwards. Therefore, in the down-cutting mode, in the time from the moment when all segments are engaged in cutting contact the rock to the moment they exit the rock, the consumed energy tends to decline.

At all stages of cutting, fluctuations can be observed in energy consumption values that can be attributed to discontinuities in the block, and to changes in the micro and macro physico-mechanical properties of the rock. After examining more than 400 cutting cycles, it was concluded in the present study that energy fluctuations must be turned into an advantage. In other words, energy consumption values can be reduced with a control system that increases the feed rate when energy values decrease, and vice versa. An auto start-stop feature, so to speak, can reduce the overall energy consumption values, as lower energy consumption values indicate a zone in which the cutting of the stone is easier, when the feed rate of the machine can be increased. Higher energy consumption values, on the other hand, indicate a zone where it is more difficult to cut the stone, when the feed rate of the machine can be lowered. Savings can be achieved both in the energy consumed and in the time spent for cutting with the aid of a variable speed control system.

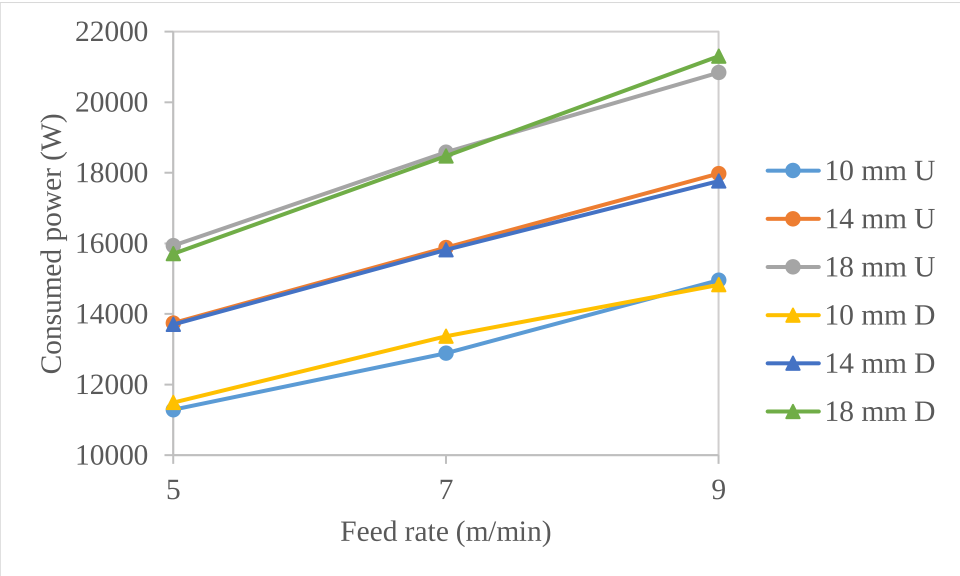
The total energy consumed in the up-cutting zone tends to be lower than the energy consumed in the down-cutting zone. Thus, if the machine stability and cutting surfaces are as desired, it would be more advantageous to cut in the up-cutting mode. Previous studies have reported that the down-cutting mode creates relatively larger vertical forces and relatively smaller horizontal forces, when compared to the up-cutting mode, and thus creates problems in the stability of the machine [2]. In the up-cutting mode, machine stability can be a problem in laboratory settings when small pieces are cut, as the workpiece materials used in laboratories are very small pieces of rock (usually much smaller than 0.25 m^3), and depending on the cutting depth and feed rate, the forces acting upon the saw blade may move the small-weight workpieces. In industrial granite cutting operations, on the other hand, in which 3–8 m^3 blocks are cut (approximately 8–22 tons), stone-machine stability is not a problem as the block is fixed to the carrier, and its own weight prevents movement.

Looking at the entire cutting process, energy consumption values, on the whole, are higher in the down-cutting mode. This is confirmed by other studies in the literature [4,9]. During up-cutting, the cutting forces and force ratio are higher than in down-cutting. In up-cutting, the vertical cutting forces are 3–5 times greater than lateral forces, while in the down-cutting mode, the vertical forces are 6–8 times greater than the horizontal forces [10].

In general, however, there is little variation in the specific cutting energy values or consumed energy values of the both of cutting modes.

Because of the diameter of blade and cutting depths, the forces acting upon the saw blade did not play a dominant role. Accordingly, it was found in the present study that energy consumption values in the two modes were very close to one another, contrary to the findings of laboratory-scale studies, which use relatively smaller saw blades (max diameter 600 mm) and observe significant differences.

At the same depth of cut values, if the V_f value is increased, energy consumption values tend to increase in all cutting modes (Figure 4), consistent with literature on natural stones. However, in the present study, another condition was analyzed that has not been covered in previous laboratory-scale studies in literature, namely the extent to which energy consumption values are affected by cutting depth under industrial cutting conditions.



U: Up cutting mode, D: Down cutting mode

Figure 4. Change in consumed power in the up- and down-cutting modes by feed rate

Cutting depth and the energy consumed relationships for cutting process can be explained as follows for different cuttings depths and feed rates: when 10 mm depth of cut, when the V_f is increased from 5 to 9 m/min (increased by 1.8 times), energy consumption increases from 11287 W to 14956 W (increases by 1.3 times) (Figure 5). Energy consumption value increases by 1.3 times instead of 1.8 times. Increasing the feed rate from 5 to 9, that is to say, cutting 4 more meters a minute, is highly advantageous in terms of production and energy costs, bringing savings in labor, total production time and energy consumption. This is very important for cutting efficiency, and the same applies to all cutting depths (10, 14 and 18 mm). In other words, in 18 mm depth of cut, when the V_f is increased from 5 to 9 m/min, energy consumption increases by 1.32 times, not by the rate of increase in the feed rate. This is true for all cutting processes, be it in the up-cutting more or the down-cutting mode

Another finding of the study concerns the change in energy consumption values when the V_f is kept constant but the cutting depth is varied. As Table 4 shows, when the feed rate is 5 m/min and the depth of cuts are 10, 14 and 18 mm, the energy consumption values are 11287, 13743 and 15704 W, respectively. When the cutting depth is increased by 1.8 times (from 10 to 18 mm), the energy consumption value increases by 1.39 times. This means that in a cutting operation with 10 saw blades, a channel is cut that is 80 mm deeper (8 mm x 10 saw blades) with each movement of the saw blades. This would result in increased production while using less energy in each cycle. Of course, if the speed were to be increased, saw blade wear would become an important issue. If the time and energy savings obtained by deeper and faster cutting compensate for the additional costs due to saw blade wear, however, the operator or the production engineer should always choose to cut faster and deeper. In industrial applications, the main goal in natural stone processing is always to find the saw blade set-up that cuts deeper and faster. In particular, natural stone plants that always cut the same type of rock achieve the optimum saw blade-segment composition, and disregard the wear. This is because the unit sale prices of granites usually compensate for the costs arising from wear.

3.2. Specific Cutting Energy

Specific cutting energies, calculated on the basis of the cutting depth, feed rate and power consumption values recorded for each cutting condition, are reported in Table 5.

Table 5. Specific cutting energy (J/mm^3) values by feed rate and depth of cut

	d (mm)					
	10		14		18	
Feed rate (m/min)	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**
5	0.1568	0.1596	0.1337	0.1359	0.1212	0.1230
7	0.1346	0.1395	0.1178	0.1187	0.1071	0.1073
9	0.1176	0.1185	0.0998	0.1010	0.0911	0.0931

The depth of cut is kept 10 mm and the V_f is increased, the SE_{Cut} value increases in both the up- and down-cutting modes, and this is true for all cutting depth values (10, 14 and 18 mm). This fact is ascertained from the formula used to calculate specific cutting energy in natural stone cutting processes. Even without making any measurements, we can predict that specific cutting energy will decrease as a result of increases in feed rate and cutting depth. Thus, specific cutting energy can be treated as a simple indicator of cutting performance, as in natural stone cutting processes the machine consumes energy from the moment it starts cutting the stone until it returns back to its start position. As this study shows, however, there are idle times when the saw blade is not cutting as it first approaches the block, and as they exit the block and return, and as they exit the block one more time and start another cycle. During these times, energy consumption continues, although the specific cutting energy value is zero as the volume of stone cut is zero. As such, cutting efficiency and cutting performance should be evaluated for the entire process, taking the energy consumed during idle times also into account.

The SE_{cut} value, which was 0.1568 J/mm^3 when the V_f was 5 m/min and the depth of cut (d) was 10 mm, reduces to 0.1230 when the cutting depth value is increased to 18 mm. The SE_{cut} value declines when either the feed rate or the cutting depth is increased. This is because of the equation used to calculate specific cutting energy. In Equation 1, the feed rate and cutting depth are denominators or divisors, while power consumption, on the other hand, is a numerator. As the d and V_f increase, so does the power consumption, but the rate of increase is smaller, resulting in smaller specific cutting energy values (Figures 5-6).

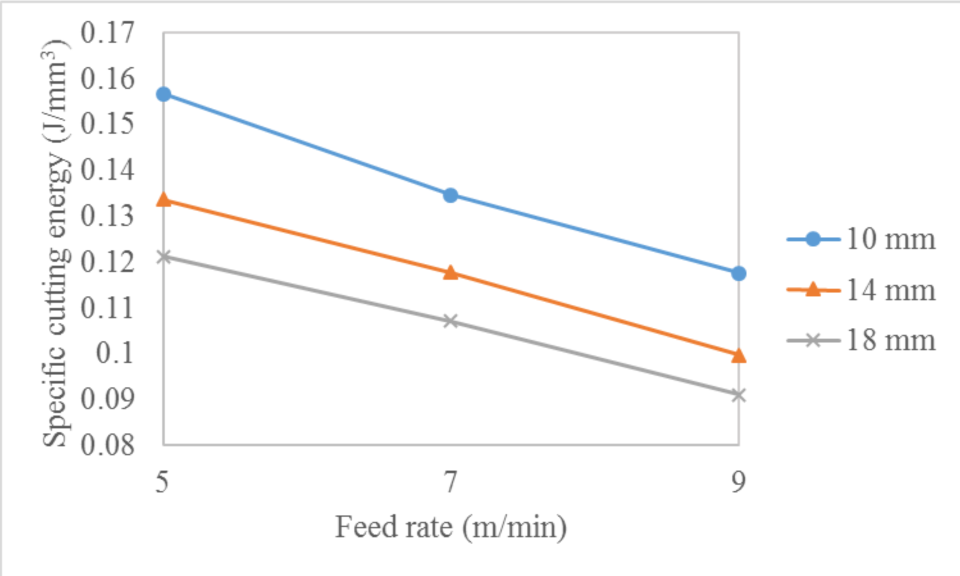


Figure 5. V_f-SE_{cut} relationship under up-cutting conditions.

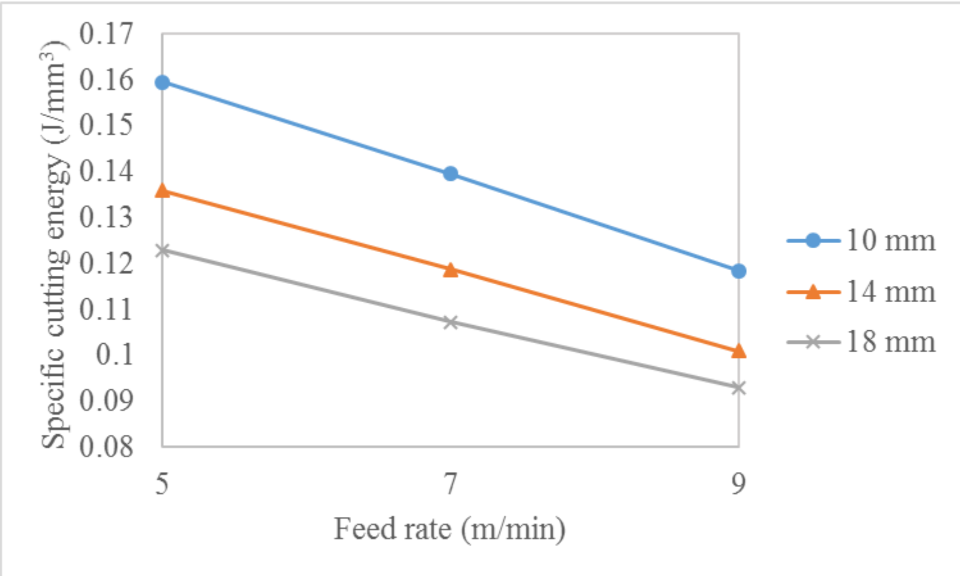


Figure 6. V_f-SE_{cut} relationship under down-cutting conditions.

4. CONCLUSION

Energy crises and other economic crises in recent years have required the entire natural stone sector to move toward efficient and sustainable production, however producers tend to disregard energy consumption, and prioritize increased cutting speeds to meet their order schedules.

The cutting speed, or feed rate, as the most important factor dictating production speed, indirectly influence labor costs through its effects on production time, which is never constant. The feed rate, which is lower at the beginning, depending on the condition of the segment, increases toward the middle of the segment's lifetime. As such, the most important parameter that can be altered by the operator or production engineer, besides feed rate, is the idling times at the beginning, return and end positions of the cutting cycle. This study analyzed the entire cutting process, dividing it into eight separate zones based on energy consumption values, and identifying the zones in which idling times can be minimized.

The saw blades used in laboratory-scale studies in literature differ in terms of the body structure, segment structure and body-segment connection. Laboratory-scale studies use saw blades with a maximum diameter of 600 m, whereas the blades used in the industry for the cutting of slabs from blocks have diameters of 1000–2000 mm, as well as different body structures, different segment structures and different water channels. Almost all studies in literature to date have sought to optimize the process by focusing on saw blade costs or the wear process. In practice, however, plant operators pay little attention to the wear process, as having produced thousands of square meters of slabs, they have generally already resolved the wear process and identified the optimum saw blade composition. From this point onwards, what matters is running the cutting process as rapidly as possible and cutting the required amount of stone in time, and occasionally disregarding wear. This is because small and medium-scale industrial cutting plants that do not work with a single type of stone do not change their saw blades depending on the type of stone ordered, and tend to use the same blade to cut multiple different types of rock, as the unit sales prices of cut stones are much greater than those of saw blades.

After achieving the optimum wear values over the years, a saw blade can cut 3000–5000 m2 of stone, translates into a cost of USD 0.08 per square meter (based on 2020 prices in Turkey). This figure is quite small when compared to energy and labor costs, which means that saw blade wear is usually disregarded. This study has examined, for the first time under industrial conditions, all power consumption values in a granite cutting process by dividing it into zones. The specific cutting energy, which is considered to be most important indicators of cutting efficiency and cutting performance in granite cutting processes, is examined under industrial conditions. Furthermore, a new perspective is developed regarding the specific cutting energy, motivated by the fact that in industrial cutting processes, the goal is not to minimize the energy consumed in a single cutting cycle, but to optimize efficiency in the use of saw blades and in production in general.

The following conclusions can be drawn from the results of this study:

- The most important parameters when measuring cutting efficiency and cutting performance in natural stone cutting processes are the total number of cycles for the target cutting amount, the idle time in each cycle and the total machine efficiency, in addition to the widely used parameters of consumed power and specific cutting energy. The greater the number of cycles, the longer the total idling time, and the more energy consumed when idling.
- Cutting efficiency and cutting performance must be evaluated on the basis of the entire cutting process. The idling time of the cutting machine also needs to be taken into consideration.
- Higher feed rates and cutting depths may provide advantages in terms of labor and energy costs, however, faster and deeper cutting increases wear, and increases the risk of the cutting surfaces not being as desired. Moreover, the balance of the saw blades can be affected, rendering them unusable, and unbalanced saw blades can also damage the machine (mill, body, etc.) in multi-blade cutters. It is necessary to establish a balance between V_f and depth of cut on the one hand, and blade life and cutting costs, on the other.
- Saw blade costs will increase in deeper and faster cutting conditions. In this case, labor costs will be saved as cutting time is shortened. In this case, deeper and faster cutting would be more advantageous.
- When the depth of cut is kept constant and the V_f is increased, the energy consumption values tend to increase, which is consistent with the findings of previous studies relating to natural stone processing. That said, it has not been previously established to what extent energy consumption values are affected by depth. A 1.8-fold increase in depth of cut produces a 1.3-

fold increase in energy consumption – and this is true for all cutting depth values. At a 18 mm depth of cut, when the V_f is increased from 5 to 9 m/min, energy consumption increases by 1.32 times, not by the rate of increase in feed rate (1.8 times). This is true for all cutting operations, be it in the any of cutting mode. This implies that cutting deeper and faster can produce benefits in terms of energy savings and efficiency in production.

- As the rate of increase in energy never equals the rate of increase in cutting depth or feed rate, cutting deeper and faster always produces smaller specific cutting energy values. Therefore, if used on their own, specific cutting energy values can be misleading when evaluating cutting efficiency and cutting performance in natural stone cutting processes.
- Power consumption values can be considered an important indicator of cutting performance. It is shown in the present study that the rate of increase in the feed rate does not equal the rate of increase in energy consumption. Therefore, using one cutting cycle instead of three cutting cycles to achieve the desired cutting depth consumes less energy, and also produces shorter cutting times, translating into time and labor savings.
- Using contemporary technologies, saw blades move within the rock at a constant speed. This study proposes a variable feed rate for saw blades that depends on the cutting zones defined, which can lead to additional energy savings.
- At all stages of cutting, both in the up-cutting and down-cutting modes, fluctuations are observed in energy consumption values that can be attributed to discontinuities in the block, and to changes in its micro and macro physico-mechanical properties. After examining more than 400 cutting cycles, it was concluded in this study that energy fluctuations must be turned into an advantage. In other words, energy consumption values may be reduced with a control system that speeds up the machine when energy values are decreased, and slows it down when energy values are increased.
- When reporting specific cutting energy values in natural stone cutting processes, the number of saw blades must be specified, as in practice, different numbers of saw blades can be run using the same motor power, depending on the cutting conditions. The block cutter used in this study had 10 saw blades that cut simultaneously, although the same machine can have between 2 and 12 saw blades installed, using the same motor power. In this case, energy consumption values would be very close to one another, but up to six times more cutting can be carried out.
- In block cutting operations, there are idle times when the saw blades are not engaged in cutting – as they first approach the block, as they exit the block and return, and as they exit the block one more time and begin another cycle. At these times, energy consumption continues, but the specific cutting energy value is zero as the amount of stone cut is zero. Accordingly, the times when the saw blades are consuming energy but not cutting must also be taken into account when evaluating cutting performance, either in the form of the total time spent cutting or the total number of cycles.
- Further studies may analyse total energy consumption efficiency in natural stone cutting processes, taking into account both the cutting and non-cutting energy consumption values.

CONFLICT OF INTEREST

The author stated that there are no conflicts of interest regarding the publication of this article.

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