Development of Cuttability Chart for a Marble Cutting with Monowire Cutting Machine

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ABSTRACT

Monowire block cutting machines can be used for natural stone block squaring operations and slab cutting operations from natural stone blocks. The efficient use of these machines reduces operating costs by ensuring less diamond wire wear and longer wire life at high speeds. The purpose of this study is to develop cuttability chart for real marble sample based on unit wear and unit energy in monowire cutting system and also perform cutting optimization. For this purpose, the full automatically servo controlled monowire cutting system which can cut blocks in three dimensions were developed in Hacettepe University Mining Engineering Department. Cutting experiments were performed at different wire rotation speed (peripheral speed) and wire downward movement speed (cutting speed) on the real marble block which was transported to the laboratory. A cuttability abacus in monowire cutting system taking into consideration the unit energy consumption during cutting operation and unit wear on diamond beads was developed with Design Expert 7.1 software for real marble sample by using the results obtained.

KEYWORDS

Monowire cutting; diamond wire; marble; wear; energy; optimization.

INTRODUCTION

Diamond wire cutting machines are indispensible machines used in several stages ranging from marble block production in natural stone quarries to the final product in processing plants. Today these machines are widely used in natural stone quarries and have evolved continuously in line with the consumers' demands so far and have opened a new era in natural stone mining [1, 2]. Generally, the diamond wire cutting method is used in natural stone quarries and decorative cutting tests, cutting and lifting basic construction structures, railway bridges, old concrete chimneys and dams [3].

The process of reducing large or irregularly shaped blocks produced in natural stone quarries to commercial size or arranging randomly sized blocks into cube or rectangular parallelepiped shapes is called 'block sizing' or 'squaring'. Various machines are used in the squaring process on blocks taken from quarries where marble and limestone production is performed [4]. One such machine is the mono-wire block cutting machine, which is important for sizing natural stone blocks and of slab-sawing from the blocks.

In plants where cutting processes are performed, the aim is to manufacture products of the desired quality at the lowest possible cost. The most important performance parameters affecting the economy of mono-wire block cutting are the energy consumed and the wear of diamond beads during cutting. Wear is important as it decreases cutting efficiency and reduces wire life [3].

Until today, many researchers have studied the machine parameters used in cutting and the properties of the material to be cut. Some researchers investigated wire structure and the number of beads on the wire [2-3], the dimensions of the marble block to be cut [5-6], cutting geometry [2, 7], bead structure [2, 6-10] and diamond wire cutting [11-13].

Although there are several studies about diamond wires in the literature, the number of studies about mono-wire cutting machines is limited. Researchers investigated effective parameters on cutting; [4, 14-16]; cutting hard materials [14, 17-18]; bead shape, structure and type [15-16, 19-20] and bead wear [4, 19, 21].

When the studies on mono-wire cutting systems are assessed, it is understood that there are no computer-controlled precision machines and that no cutting optimization has been performed on the basis of unit wear and unit energy values. Therefore, the cutting performance in mono-wire cutting machines should be analyzed in detail depending on operating parameters. This type of work is only possible with a computer-controlled precision machine. This study aims to investigate the effect of wire rotational speed (peripheral speed) and wire descending speed (cutting speed) on cutting performance parameters (i.e. unit wear and unit energy) in real marble cutting. Furthermore, using the obtained results, it is also intended to create cuttability charts and perform cutting optimizations for real marble sample on the basis of unit energy and unit wear values.

To achieve these goals, a computer-controlled, fully automatic cutting machine was initially developed in the Mining Engineering Department of Hacettepe University. Some experiments were then performed with a fully automatic, computer-controlled mono-wire block cutting machine on real marble sample selected from natural stone quarry located in Turkey. Subsequently, the effects of wire peripheral speed (PS) and cutting speed (CS) variations on cutting performance parameters were investigated. On the basis of a statistical analysis of the obtained data, cutting charts were created and optimum cutting points were determined by considering the unit wear and unit energy for real marble sample. A lack of this type of optimization work in the natural stone industry means that rocks in these facilities are not cut using the proper parameters. With this study, it was intended that the appropriate cutting parameters would be determined for the rock to be cut.

1. EXPERIMENTAL STUDY

1.1. Mono-wire Block Cutting Machine

Mono-wire block cutting machines can be used for squaring natural stone blocks and slab-cutting processes on the blocks. In facilities where these cutting processes are performed, the aim is to manufacture products of the desired quality for the lowest possible cost. With these machines, cutting is performed using diamond wire. The use of diamond wire in the mono-wire cutting process ensures a low degree of diamond wire wear and a longer wire life while helping to perform cuts at high cutting speeds, thus reducing the cutting costs. Therefore, when this machine was designed, it was equipped with various sensors and measuring devices.

The designed and manufactured mono-wire block cutting machine (Figure 1) was composed of four main units:

- Mechanical unit
- Hydraulic unit
- Electrical and electronic unit
- Automation unit

The mechanical unit comprised eight motors and a gearbox that provided movement to the wire. A wagon and bridge system and screw shafts provided the up-down motion system for the pulleys. The hydraulic unit consisted of a hydraulic motor providing power and a cutting deck to move around the wire axis. A tensioning system applied tension on the wire. The electrical and electronic units included load cells, vibration gauges, a flow metre, bridge termination switches (to terminate the movements of the wagon and bridge) and a control panel. The automation unit comprised a computer that provided automatic control of the mono-wire cutting machine [4].

Fig. 1 General view of the mono-wire block cutting machine.

1.2. Methodology

The purpose of this study was to develop cuttability charts on the basis of unit wear and unit energy observed during the cutting of Mugla Lilac real marble block with a computer-controlled mono-wire cutting system and optimize the cutting process. Therefore, the cutting of real marble sample brought from Mugla was performed with the mono-wire cutting machine operated at different peripheral speed (PS) and cutting speeds (CS). Cutting angle values of the wire-driving pulleys were constant. Cutting charts were formed on the basis of the energy consumed during cutting and the wear that occurred on the diamond beads in the cut and at optimum cut points that were determined according to unit wear and unit energy. Some physical and mechanical properties of the sample used in the study determined according to ISRM [22] are given in Table 1.

Table 1. Physical and mechanical properties of Mugla Lilac

UWV (g/cm^3)	AP (%)	UCS (MPa)	TS (MPa)	IS (MPa)	BAR ($cm^3/50cm^2$)
2.73	0.23	89.1	8.5	3.0	13.26

UWV: Unit Volume Weight; AP: Apparent Porosity; UCS: Uniaxial Compressive Strength; TS: Tensile Strength; IS: Impact Strength; BAR: Bohme Abrasion Resistance

At the beginning of the study, the parameters to be set during the cutting operations were determined. In this context, the peripheral speed and cutting speed values used in previous studies (from the literature), the speed values of machines used in industry and the limits of the machine developed for this study were considered. As a result of these investigations, a 25–35 m/s interval was chosen as the wire rotation speed and a 10–20 mm/min interval was chosen as the cutting speed. In the tests performed in this study, the operating parameters used were applied according to the layout shown in Figure 2.

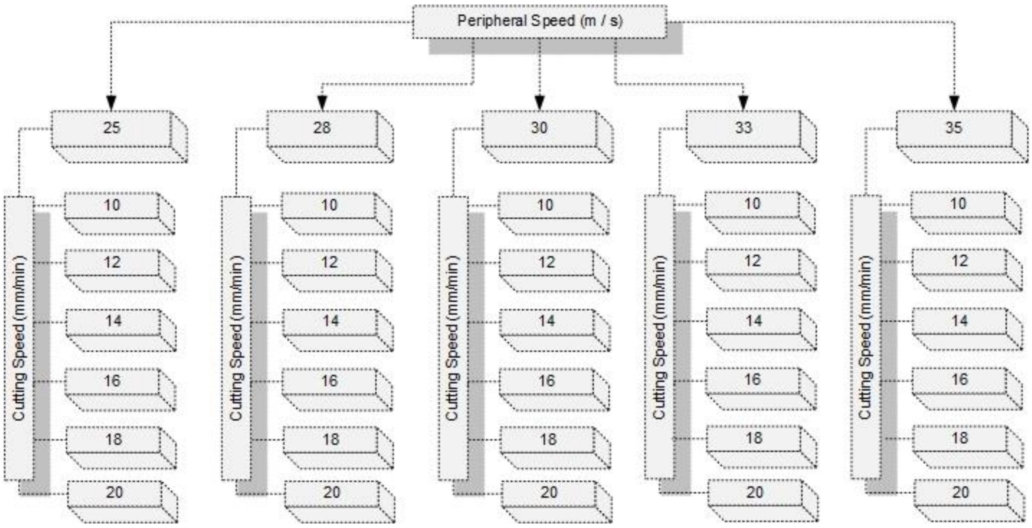

Fig. 2 Peripheral and cutting speed values at which the cuts were performed.

The cutting parameters given in Fig. 2 were used in mono-wire cutting experiments. In the cuts, a CC250/4 coded spring manufactured by the HRK firm and a 12 m long, plastic-coated diamond wire were used (Figure 3).

Fig. 3 Image of the diamond wire used in the experiments.

Machine parameters measured during all cutting processes:

- Reaction cutting force in the x-direction in both pulley guides (N)
- Reaction cutting force in the y-direction in both pulley guides (N)
- Tension in wire (MPa)
- Electrical Power (W)
- Vibration of wire (Hz) (in x- and y-directions)
- Water consumption (l/min)

Reactional cutting forces during cutting were measured using load cells. An energy analyser was used for instantaneous energy measurement during cutting, vibration metres were used to measure vibrations on the diamond wire and a flow metre was used to measure the amount of water used. The average amount of water used in cuttings was kept constant between 6 and 8 l/min during the cutting tests. The tensioning piston of the tensioning pulley was stressed up to 1 MPa, and this value was kept constant for all cuts. The width of the rocks cut was 1 metre. Cuts were made for 45 min.

2. STATISTICAL ANALYSIS

Within the scope of this study, Design Expert 7.1 was used for data analysis and for determining the optimum points of peripheral and cutting speed values for Mugla Lilac real marble sample. Design Expert 7.1 [23] is a widely used program which was developed for the experimental optimization process and which can effectively design the experiments in the most suitable way according to different methods. After making the experiments based on the design selected and entering the results obtained in the program, it derives the most suitable equations for dependent variables (response) and can realize the determination process of the optimum points by means of the derived equations. Identifying the optimum working points and the estimated results obtained as a result of the experiments made on these points is possible with this program. For building the models, interpolation method was used [24].

2.1 Design Summary

Before initializing the statistical analysis, information that reflects the properties of each variable regarding the factors and response was analyzed. This information is composed of the data such as mean and standard deviation for describing the frequencies about the variables and also definitions of the methods and models to be used in modeling studies. The design properties used in this study are demonstrated in Table 2 and the descriptive statistical data regarding factors and response are shown in Table 3 and 4, respectively.

Table 2. Statistical design properties of study.

Study Type	Initial Design	Design Model	Runs
Factorial	D-optimal, Point Exchange	2FI (two-factor interactions)	30

Table 3. Descriptive statistical analysis of the factors.

Factor Name	Unit	Type	Low Actual	High Actual	Mean	Std. Dev.
Peripheral Speed (PS)	m/s	Numeric	25.00	35.00	30.13	3.57
Cutting Speed (CS)	mm/min	Numeric	10.00	20.00	15.00	3.42

Table 4. Descriptive statistical analysis of the responses.

Response Name	Units	Obs	Analysis	Min.	Max.	Mean	Std. Dev.	Model
Unit Energy (UE)	kWh/m^2	30	Polynomial	1.14	2.24	1.70	0.32	Cubic
Unit Wear (UW)	$\mu m/m^2$	30	Polynomial	14.00	29.7	20.69	3.88	Quadratic

A micrometer instrument was used to perform wear measurements. Before the cuts, 20 beads were selected on the diamond wire and these beads were painted with a spray paint. At the end of the cut, the paint on the beads was erased but the paint on the plastic was not. Marked beads could be easily identified by the paint marks on the plastic. The diameters of 20 selected beads were measured two times. Measurements were made using the micrometre device in five different directions before starting the cuts, and the average of two measurements was used. Thus, the measured diameter was constant along the bead axis. At the end of each cut, the diameters of the marked beads were measured two times. The average of the differences between the diameter values before and after the cutting process gave the average wear amount on the diamond beads.

Depending on the area being cut and the cutting time, wear amounts could be found to be either very high or very low using different cutting parameters. To compare the wear values observed in different cuts, they were divided into area values for each cut and the wear occurring on the beads while cutting the unit area (i.e. unit wear values).

The unit energy term used in the study represents the amount of energy per unit area (kWh/m^2) required to cut the stone. It is calculated by multiplying the test time by the average of net power values and dividing by the surface area of the cut. Power values used in the calculations were recorded during cutting with the aid of a power analyser located on the machine. In the unit energy calculations, the average power values before the diamond wire entered the cut were determined and subtracted from the average power values during the cut. Thus, unit energy changes were determined through net energy values.

2.2 Statistical assessment related to unit wear

Statistical analysis were made for the purpose of estimating unit wear by using peripheral speed and cutting speed and the unit wear model equation was obtained. The quadratic model for Mugla Lilac, which was found to be statistically the most significant in the analysis, was chosen as the most suitable model for estimating the unit wear (Table 5). The validity of the models (quadratic) was tested with variance analysis. The results were presented in Table 6 and 7, respectively. The model based on the regression coefficients given in Table 6 is statistically significant at 99% (α=0.01) confidence level. The estimation graph of the developed model is given in Figure 4. The relationship between the observed values of the unit wear from experimental studies and the predicted values from the unit wear model was also investigated and the result is given in Figure 5.

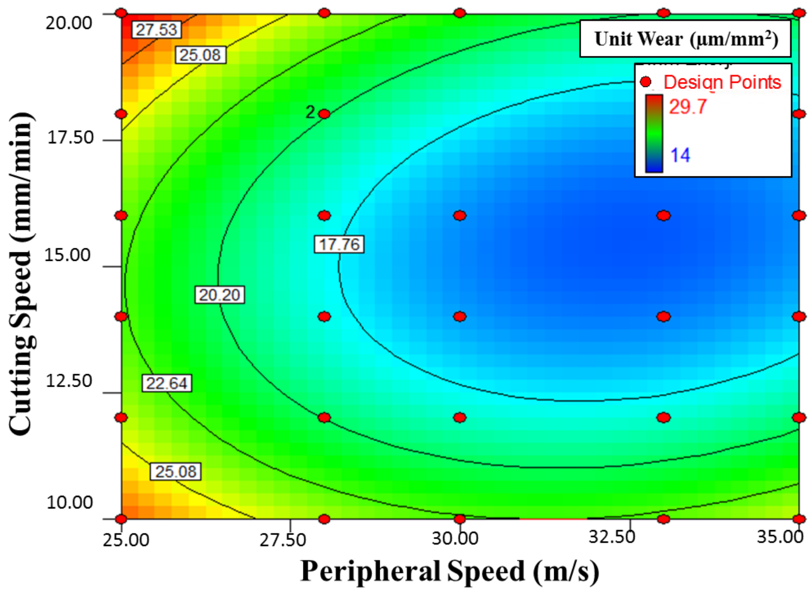

Fig. 4. The estimation graph of the unit wear model for Mugla Lilac

The equation of the quadratic model for Mugla Lilac was obtained according to Table 8 is as follows.

$$\text{Unit Wear} = 16.15 - 3.24 * (PS) - 0.53 * (CS) - 1.53 * (PS) * (CS) + 3.39 * (PS)^2 + 6.19 * (CS)^2 \quad (1)$$

Table 5. Results of the statistical analysis for selecting of suitable model for unit wear

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	
Linear	3.32	0.34	0.29	0.14	
2FI	3.29	0.37	0.30	-0.01	
Quad.	1.30	0.91	0.89	0.84	Suggested
Cubic	1.20	0.94	0.91	0.82	

Table 6. The results of the multiple regression analysis for unit wear

Factor	Coefficient Estimate	df	Standard Error
Intercept	16.15	1	0.47
(PS)	-3.24	1	0.33
(CS)	-0.53	1	0.35
(PS) (CS)	-1.53	1	0.49
$(PS)^2$	3.39	1	0.57
$(CS)^2$	6.19	1	0.59

Table 7. The ANOVA of the regression model for unit wear

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	410.27	5	82.05	48.78	< 0.0001	sig.
(PS)	159.51	1	159.51	94.83	< 0.0001	
(CS)	3.97	1	3.97	2.36	0.1374	
(PS)(CS)	16.65	1	16.65	9.90	0.0044	
(PS)2	59.47	1	59.47	35.35	< 0.0001	
(CS)2	182.95	1	182.95	108.77	< 0.0001	
Residual	40.37	24	1.68			
Lack of Fit	39.76	23	1.73	2.86	0.4401	not sig.
Pure Error	0.61	1	0.61			
Cor Total	450.64	29				

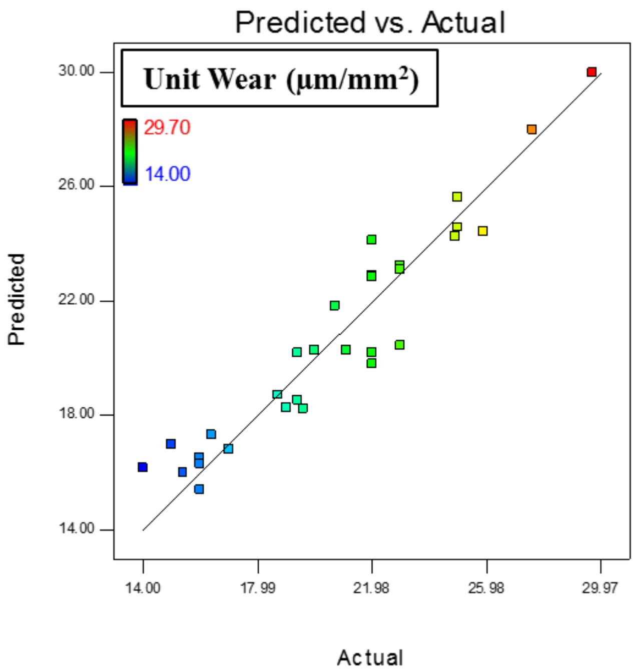

Fig. 5. The relationships between observed values from experimental studies and predicted values obtained from the unit wear model for Mugla Lilac

2.3 Statistical assessment related to unit energy

Statistical analysis were performed with different kind of models given in Table 8 for estimating the unit energy by using peripheral speed and cutting speed. The cubic model for Mugla Lilac was found to be the best models for estimating the cutting rate (Table 8). The validity of the model (cubic) was tested with variance analysis. Results of the multiple regression analysis are given in Table 9 and the results of the variance analysis are given in Table 10. The model based on the regression coefficients given in Table 9 is statistically significant at 99% (α=0,01) confidence level. The estimation graph of the developed model is given in Figure 6.

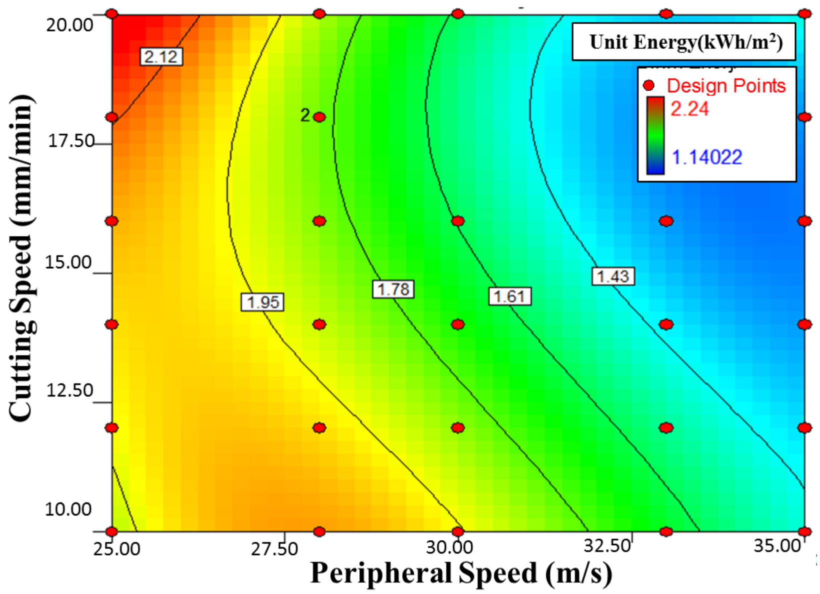

Fig. 6. The estimation graph of the unit energy model for Mugla Lilac

The equation of the cubic model for Mugla Lilac was obtained according to Table 9 is as follows.

Unit Energy = 1.65 – 0.55 * (PS) - 0.28 * (CS) - 0.10 * (PS) * (CS) + 0.01 * $(PS)^2$ + 0.12 * $(CS)^2$ + 0.28 * $(PS)^2$ * (CS) + 0.04 * (PS) * $(CS)^2$ + 0.18 * $(PS)^3$ + 0.09 *$(CS)^3$ (2)

Table 8. Results of the statistical for selecting of suitable model for unit energy

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	
Linear	0,17	0,73	0,71	0,67	
2FI	0,17	0,76	0,73	0,68	
Quad.	0,16	0,78	0,74	0,65	
Cubic	0,14	0,86	0,80	0,71	Suggested

Table 9. The results of multiple regression analysis for unit energy

Factor	Coefficient Estimate	df	Standard Error
Intercept	1.65	1	0.05
(PS)	-0.55	1	0.12
(CS)	-0.28	1	0.12
(PS) (CS)	-0.10	1	0.05
$(PS)^2$	0.01	1	0.06
$(CS)^2$	0.12	1	0.07
$(PS)^2$ (CS)	0.28	1	0.09
(PS) $(CS)^2$	0.04	1	0.09
$(PS)^3$	0.18	1	0.13
$(CS)^3$	0.09	1	0.13

Table 10. The ANOVA of the regression model for unit energy

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2.56	9	0.28	13.65	< 0.0001	Sig.
(PS)	0.43	1	0.43	20.42	0.0002	
(CS)	0.11	1	0.11	5.35	0.0315	
(PS)(CS)	0.08	1	0.08	3.65	0.0704	
$(PS)^2$	0.00	1	0.00	0.00	0.9735	
$(CS)^2$	0.07	1	0.07	3.50	0.0761	
$(PS)^2(CS)$	0.18	1	0.18	8.87	0.0074	
$(PS)(CS)^2$	0.00	1	0.00	0.22	0.6427	
$(PS)^3$	0.04	1	0.04	2.09	0.1637	
$(CS)^3$	0.01	1	0.01	0.52	0.4797	
Residual	0.42	20	0.02			
Lack of Fit	0.39	19	0.02	0.85	0.7075	
Pure Error	0.02	1	0.02			
Cor Total	2.97	29				

The relationship between the observed values of the unit energy from experimental studies and the predicted values from the unit energy model was also investigated and the result is given in Figure 7. Figure 7 indicates that the results obtained from the model well reflect the real condition.

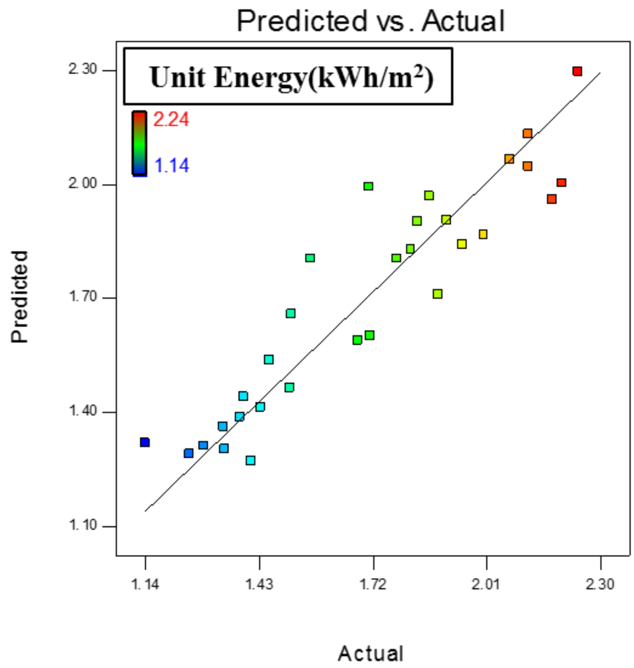

Fig. 7. Relationships between observed values from experimental studies and predicted values obtained from the unit energy model for Mugla Lilac

The results obtained from the statistical analysis show that developed unit wear and unit energy models are statistically significant and unit wear and unit energy can be modeled by these ways. By using the model equations and also estimation graphs, it is possible to estimate the unit wear and unit energy before starting the cutting with diamond wire.

2.4 Optimization

The main purpose of this study is to determine the optimum peripheral speed and cutting speed values that would minimize the unit wear and unit energy values in cutting Mugla Lilac real marble sample with monowire cutting system and also to develop cuttability charts for monowire cutting. For this purpose, the aforesaid Design Expert 7.1 program was used, and firstly the constraints were defined (Table 11). Later, the constraints were used to determine the optimum points for Mugla Lilac real marble sample.

Table 11. Design constraints for optimization

Name	Goal	Lower Limit	Upper Limit	Importance
PS (m/s)	Min.	25	35	3
CS (mm/min)	Max.	10	20	5
UW (µm/m^2)	Min.	14	29.7	5
UE (kWh/m^2)	Min.	1.14	2.24	5

The optimum point was determined by using Design Expert 7.1 program for Mugla Lilac real marble sample considering the design constraints. Numerical optimization was done by setting goals for each response to generate optimal conditions. The optimization module in Design-Expert searches for a combination of factor levels that simultaneously satisfy the requirements placed on each of the responses and factors. The results are given in Table 12.

Table 12. The optimum working conditions for sample

PS (m/s)	CS (mm/min)	UE (kWh/m^2)	UW (µm/m^2)
31.22	18.27	1.41	17.62

By using the model equations obtained from the statistical analyses, cuttability charts for Mugla Lilac real marble sample was developed with respect to unit wear and unit energy separately. The results are given in Figure 8 and 9 for unit wear and unit energy, respectively. The cuttability charts show the optimum working conditions and estimated unit wear and unit energy values that will be occurred under these conditions.

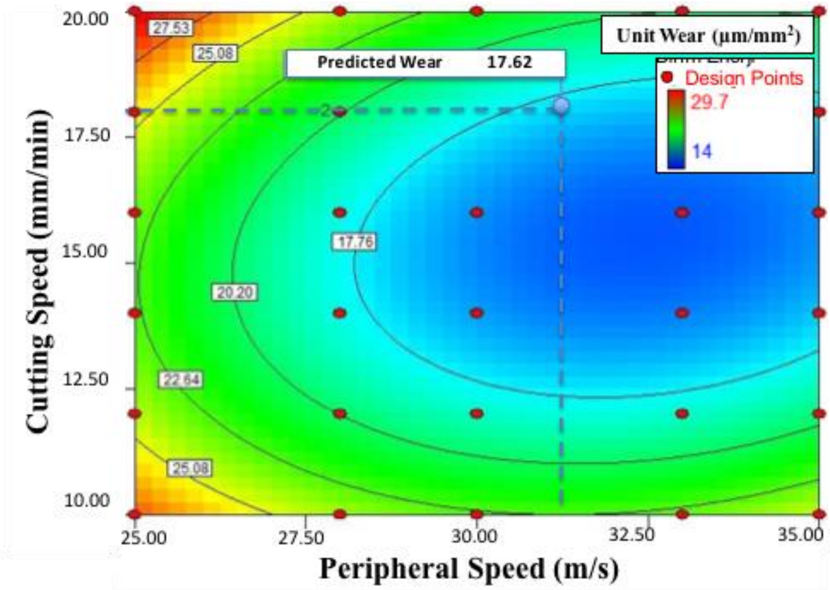

Fig. 8. The cuttability chart including the optimum conditions with respect to unit wear

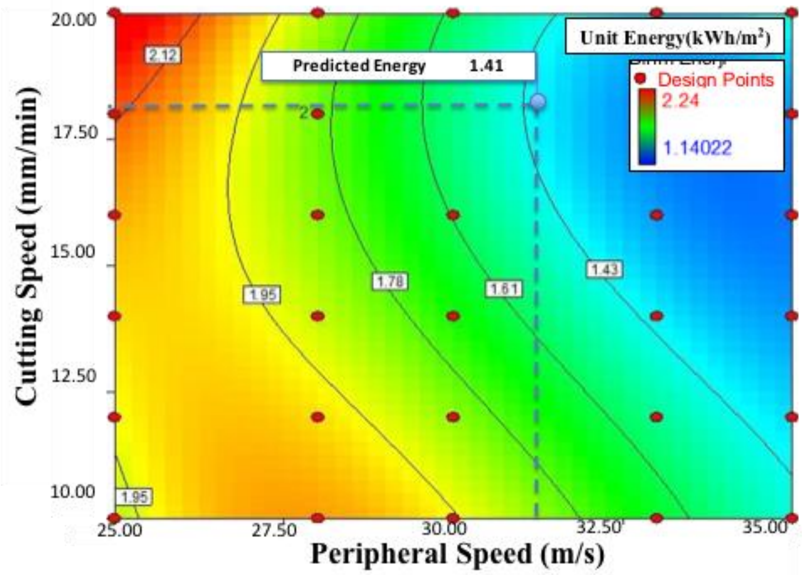

Fig. 9. The cuttability chart including the optimum conditions with respect to unit energy

By using these charts, it is easy to determine the values of the unit wear and the unit energy in different working condition before starting the cutting operation with monowire cutting machine for Mugla Lilac real marble sample.

3. CONCLUSION

In this study, determination of the optimum working conditions for Mugla Lilac real marble sample in terms of cutting performance parameters including unit wear and cutting rate and the development of cuttability charts with respect to cutting performance parameters were aimed. As a result of this study, the optimum working parameters for Mugla Lilac real marble of 31.22 m/s peripheral speed and 18.27 mm/min cutting speed were found in mono-wire cutting machine. Cuttability charts for Mugla Lilac was developed depending on the performance parameters namely unit wear and unit energy. These charts would contribute to natural stone industry for more efficient usage of mono-wire cutting machine. By using these charts, it is easy to determine the values of the unit wear and the unit energy in different working condition before starting the cutting operation with diamond wire for Mugla Lilac real marble.

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