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ORIGINAL PAPER

Investigation of the effect of boron carbide-doped diamond sockets on cutting performance in granite cutting

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Abstract
In the study, boron carbide was added to the matrix in different ratios in order to increase the wear resistance of the socket matrix and to strengthen the bond at the matrix interface with the diamond. Under the same sintering conditions, eight different tool sockets were produced. One of them is boron carbide non-doped (0% B_4C) reference socket. The others are boron carbide-doped sockets in different ratios (1-2-3-4-5-6-7% B_4C). The produced sockets were welded around a 350-mm saw to produce circular saws. In the study, firstly, the metallographic properties of the boron carbide non-doped (0% B_4C) and boron carbide-doped (1-2-3-4-5-6-7% B_4C) sockets such as theoretical densities, unit volume weights, porosity, Knoop hardness (HK), and weight wear loss were determined. Cutting experiments were then carried out (under constant cutting conditions) with eight different circular saws on a single hard stone species with a homogeneous structure. At the end of cutting experiments, the power consumption, specific cutting energy, specific abrasion, and noise levels of each saw were determined. Cutting performance of boron carbide non-doped and doped circular saws has been investigated taking into account the metallographic properties of the sockets. At the end of the study, the lowest power consumption and specific cutting energy consumption due to high porosity and low hardness were obtained at 7% B_4C-doped sockets. It was determined that the lowest specific abrasion value was found in sockets with 4% B_4C doped due to the low porosity and high hardness value, and the lowest noise level was found in 1% B_4C-doped sockets.

Keywords Diamond sockets · Boron carbide · Granite · Specific cutting energy · Specific abrasion · Noise

Introduction

Natural stone blocks produced from quarries come to marble processing plants where they are presented to the market as semi-finished or finished products. Circular saws are used for sizing of natural stones in the factory. The cost of cutting among the cost items constitutes a significant share. The most important factor in cutting cost is energy and saw cost. The energy consumption value in the cutting process varies depending on the rock and machine parameters. Physical and mechanical properties of the rock and hard mineral affect the cutting process. In addition, parameters such as cutting speed, cut depth of saw, structure of socket, and the power of the machine affect the specific cutting energy, specific abrasion, and noise. One of the biggest problems encountered in the operation of natural stones is that they shorten the life of the cutters used in natural stone cutting and cause the natural stone production costs to increase to a great extent. Determination of cutters suitable for the rocks has an important role in decreasing natural stone processing costs.

The cost of natural stone production is controlled by the largely cutter productivity, which is affected considerably by the cutting wear conditions (Ersoy and Atıcı 1999). Many studies have been done in the literature on optimization of natural stone cutting, energy estimation, socket wear, and socket construction. Some of these studies are summarized below.

Studies on specific cutting energy and cutting forces

Büyüksağiş (1998) conducted cutting tests on seven marbles and determined cutting forces and specific energy values according to the data obtained from these cutting experiments.

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Table 1 Boron carbide chemical content

Element	B	C	O	Fe	Si
%	75–77	18–21	0.1*	0.15–0.25*	0.1*

*Maximum value

Table 2 Theoretical density (TD) and unit volume weight (UVW) values of boron carbide-doped diamond sockets

%B_4C	TD (g/cm^3)	UVW (g/cm^3)	Number of experiments
0	8.34	8.05	3
1	8.15	7.56	3
2	7.97	7.53	3
3	7.80	7.34	3
4	7.62	7.30	3
5	7.47	6.82	3
6	7.29	6.42	3
7	7.06	6.05	3

Using multiple regression technique, empirical approaches have been developed to determine the required cutting force and specific energy values by rock properties. Xu (1999) conducted cutting experiments with five different granites in a circular sawing machine. In these experiments, shear forces and specific shear energy values are calculated. In addition, it was determined that the surfaces of the granite samples were examined under the microscope and the energy consumed in the cutting was increased due to the increase of the rock friction coefficient. Karakuş (1999) performed performance measurements on four different rocks on block cutting machines in the marble factory and examined the cutability parameters of marbles. In the study, the relationship between the physico-mechanical properties of the rocks and the cutting energy was investigated. Büyüksağiş and Goktan (2005) considered specific energy as a criterion for cutting efficiency and conducted cutting tests to determine optimum cutting conditions for seven different marbles. In the study, specific cutting energy was correlated with Cerchar abrasion index, Mohs hardness, and uniaxial compressive strength by multiple regression analysis. Atıcı (2005) performed cutting experiments on 10 different rocks at different cutting depths, different cutting speeds, and different peripheral speeds. The relationship between the rock properties and the specific cutting energy and the wear rates of the saws are investigated. Büyüksağiş (2007) conducted cutting experiments on six granite samples with circular saws up and down. The specific energy and specific abrasion values in the sockets are calculated in the cutting experiments. Empirical approaches between specific energy and specific abrasion values are revealed using multiple regression analyses. Güneş Yılmaz and Göktan (2008) performed cutting experiments on two different granite samples. In this study, the effects of cutting depth and cutting speed on cutting forces, power consumption, and specific energy are investigated. Şengün et al. (2009) conducted cutting experiments using four different magmatic rock types. They calculated the specific cutting energy for each rock type from the data obtained in the constant cutting parameters. They performed regression analyses to determine the effect of the physical and mechanical properties of rocks on cutting energy. In the cutting process, the porosity and compressive strength of the rocks play an important role. Yurdakul and Akdaş (2012) calculated the specific shear energy values in order to determine the cutability of six different carbonate sources in seven different block cutting machines in three different natural stone processing plants. The relationships between the physico-mechanical properties of the rocks and the specific cutting energy values are investigated by statistical analysis.

Researches on socket wear

Xu et al. (2002) evaluated horizontal and vertical forces on diamond grains by performing cutting tests on two different types of granites. The temperature formed in the diamond-granite cutting zone was measured by thermocouple. They have determined that this measured temperature value is important for diamond wear. Eyuboglu et al. (2003) determined the physico-mechanical properties of 24 andesite blocks extracted from the same marble quarry. After the block cutting operations in the factory, they determined the wear rates in the saw. They investigate the relationship between the specified abrasion rates and the physico-mechanical properties of the rock. Polini and Turchetta (2005) performed cutting experiments on two different granite samples with two different

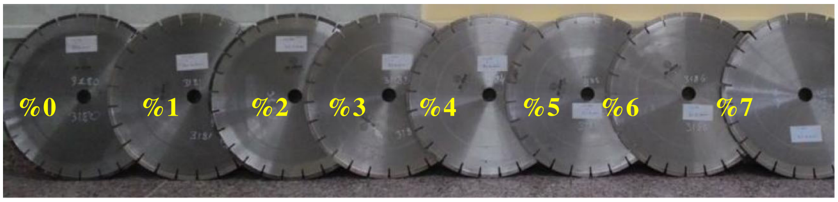


Fig. 1 Appearance of circular saws with boron carbide additive and additive diamond inserts

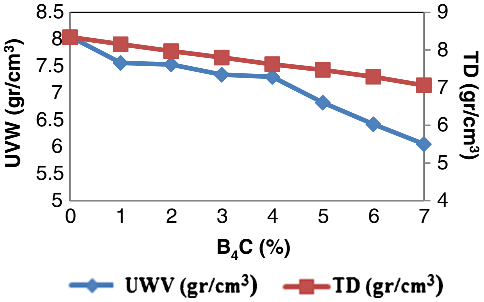


Fig. 2 Effect of boron carbide additive on unit volume weight and theoretical density

Table 3 Porosity values

%B_4C	Porosity (%)	Number of experiments
0	3.48	3
1	7.24	3
2	5.52	3
3	5.90	3
4	4.20	3
5	8.70	3
6	11.93	3
7	14.31	3

saws. After the cutting tests, they have determined the abrasions in the saws with both diametrically and with weight reductions. The relationship between saw wear values and the volume of material produced during cutting is shown. Özçelik et al. (2008) have performed cutting experiments with sockets produced at different diamond concentrations. They determined that the unit wear decreased with the cutting depth and the increase in diamond concentrations.

Researches on noise

Şengün et al. (2010) determined the noise levels in various marble processing plants and compared them with the limit values. At the end of the study, they determined that the noise level in the marble processing plants is higher than the limit values for continuous operation. Şengün et al. (2013) performed cutting experiments on 10 different rocks. In the cutting experiments, they measured the noise values and the saw cycle during cutting of the saw. The relationships between the physical and mechanical properties of the rocks and the saw cycle and noise values are statistically investigated. They emphasized that work safety and worker health precautions should be increased in the cutting processes of hard and high strength rocks. Güneş Yılmaz (2013) has carried out cutting experiments with two different saws, the sandwich-core saw, and the conventional saw, on the Blue Pearl granite sample.

Fig. 3 Appearance from unit volume weight experiments

In the cutting experiments, the effects of the saws on the specific wear rate and noise emission were investigated. As a result of the cutting experiments, it was determined that the sandwich-core saw had a lower specific wear rate and the average sound level was about 10 dB lower than the conventional saw.

Studies on socket matrix

Luo and Liao (1995) investigated the effect of diamond type and grain size on cutting performance. They performed cutting tests on granite samples with fine-grained and coarse-grained diamond saw blades with the same concentration. It has been determined that fine-grained diamond sockets perform better than coarse-grained diamond sockets for hard rocks.

However, they have shown that fine-grained diamond sockets have higher cutting force values than coarse diamond sockets. Li et al. (2002) emphasized low wear, low energy consumption, and high shear efficiency for low-cost cutting in granite cutting in circular saws.

They pointed out that the amount of wear in the sockets is related to machine parameters, diamond tool surface, and rock properties. Experimental studies have been carried out on granite specimens with sockets made of Ti-Cr-coated diamond grains. Xu and Yu (2005) used Ti-Cr-coated and uncoated diamond beads in three different matrix structures and performed cutting tests on a single granite sample. After cutting tests, they determined that wear values of Ti-Cr-coated sockets decreased.

Studies using boron doped in socket matrix

Hwang et al. (2005) have used boron-doped nickel aluminum instead of cobalt in socket matrix. At the end of the

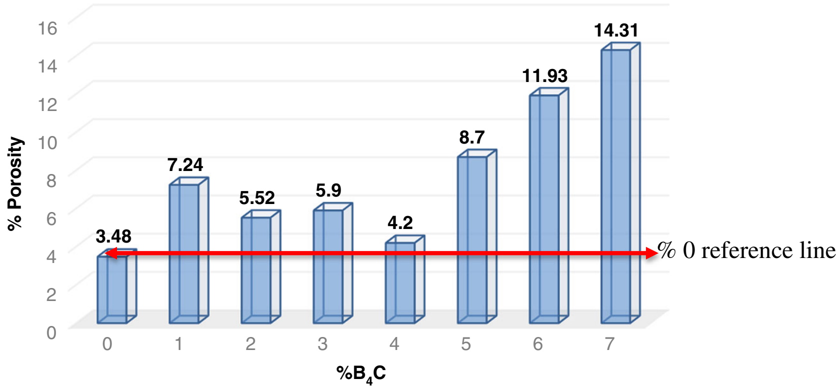


Fig. 4 Porosity change according to boron carbide doped

study, it was determined that the hardness and tensile strength of boron-doped sockets increased. However, cutting performance of boron-doped sockets has not been determined in the study. Özel et al. (2009) produced Cu-Al-B_4C metal matrix composites under the same sintering conditions by adding 5%, 10%, and 20% B_4C into Cu-5% Al powder mixture. They have examined the microstructures of the pressed samples. The hardness values were also measured and the highest hardness values were determined in the sample with 20% B_4C addition. Öksüz et al. (2011) produced two types of marble sockets with the same cobalt and iron ratios, keeping diamond concentrations and bronze ratios constant. They added 0.7% B_4C to these two types of socket matrix and investigated the effect of B_4C addition on socket hardness and abrasion resistance. Brinell hardness values were measured at five different points of each composite material under 100 kgf force and mean hardness values were determined. It was shown that the matrix hardness decreased with Fe addition, but matrix hardness increased with B_4C addition. Islak et al. (2012) examined the effect of boron carbide additives on the microstructure and mechanical properties of diamond sockets. They produced four different sockets with 0%, 2%, 5%, and 10% boron carbide added. The sockets were manufactured at 700 °C, under 35 MPa pressure and 3 min of sintering. As the ratio of boron carbide increased, hardness increased but bending strength decreased.

Fig. 5 View from Knoop hardness experiments

When the scientific studies on the cutability of rocks are examined in literature, it is seen that the relations between mineralogical, physical, and mechanical properties of rocks are taken into consideration by cutting parameters such as saw diameter, saw cycle, cutting depth, feed rate, cutting forces, specific cutting energy, and specific wear.

In the studies on the development of socket matrix, the parameters of socket production such as sintering time, temperature, and pressure have been changed. Furthermore, the addition of different metals (Co, Mb, Ti) to the matrix structure, the effects of diamond ratios, and sizes have also been investigated by many researchers. However, these studies have been limited to metallographic investigations and the cutting performance of the diamond socket saws has not been determined.

Table 4 Knoop hardness (HK) values

%B_4C	HK
0	244.47
1	241.58
2	253.35
3	279.13
4	303.46
5	244.67
6	234
7	242

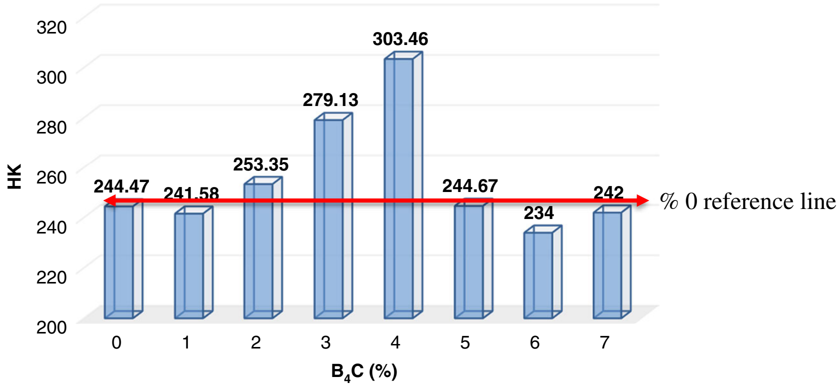


Fig. 6 Knoop hardness (HK) value change according to boron carbide doped

In this study, besides determining the metallographic properties of boron carbide-doped sockets different from the literature, cutting tests were performed under the same conditions and cutting performance was determined.

Boron carbide

Boron carbide is an important boron end product with a high market volume among hundreds of boron chemistries worldwide (Alp et al. 2013). Boron carbide is used in the processing of ceramics and hardworking materials such as saws, as well as finding space in various fields depending on their physical properties (Karaçay 2008).

To increase the wear resistance of the metallic matrix and to strengthen the bond at the matrix interface with the diamond, carbides are added to the matrix. Recently, boron carbide, which has high melting point, high hardness, low density, high chemical stability, and excellent mechanical properties, is an important material for advanced technology. Boron carbide is the hardest material known after diamond and cubic boron nitride. Due to its high hardness, abrasion is used to improve the resistance (Pierson 1996; Ma et al. 2010; Islak et al. 2012).

In the natural stone sector, the shortage of sockets used especially for the cutting of hard natural stones of granite type and the increase of the production cost per square meter as a result of this constitutes a serious problem. In the scope of the study, boron carbide was also supplied and used in the socket matrix in order to increase the resistance against wear of the diamond socket. In Table 1, the chemical content of boron carbide used in diamond sockets is given.

Experimental studies

In the scope of the study, firstly, a reference saw is produced with 0% (B_4C) without an additive boron carbide. Subsequently, boron carbide-added sockets were produced in seven different percentages (1-2-3-4-5-6-7 B_4C). The obtained diamond sockets were welded around a circular plate with a diameter of 350 mm and circular saws suitable for granite cuts were produced. The sockets were manufactured at a temperature of 730 °C and a sintering duration of 3 min under a pressure of 35 MPa. The appearance of circular saws with boron carbide-added diamond inserts is given in Fig. 1 (Ekincioğlu 2017).

Fig. 7 Wear test set

Fig. 8 Measurement before and after wear

Table 5 Weight wear loss test results

%B_4C	Weight wear loss (g)
0	0.00374
1	0.00500
2	0.00445
3	0.00450
4	0.00297
5	0.00643
6	0.00628
7	0.00768

Within the scope of experimental studies, theoretical densities, unit volume weights, porosities, Knoop hardnesses (HK), and weight loss values were determined in order to determine the metallographic properties of boron carbide-doped diamond sockets. Later, cutting tests were carried out on a single granite type with constant cutting parameters such as cutting depth, feed rate, saw peripheral speed, and the amount of water. As a result of cutting tests, net power consumption, specific cutting energy, specific wear, and noise values of circular saws were determined. According to the results obtained, cutting performance of boron carbide-doped sockets was determined.

Metallographic properties of boron carbide-doped diamond sockets

Theoretical density and unit volume weight

The unit volume weight values of boron carbide-doped diamond sockets are determined according to ASTM B 311-08 standard (ASTM 2009). The theoretical densities of boron carbide-doped diamond sockets are calculated according to the boron carbide, cobalt, nickel, bronze, and diamond ratios in the matrix. The unit volume weights (UVW) and the theoretical densities (TD) of the boron carbide-doped diamond sockets are given in Table 2.

It was determined that the unit volume weight decreased with the increase of the amount of boron carbide. This is due to the low boron carbide density (2.52 g/cm^3) compared to cobalt (8.90 g/cm^3), nickel (8.85 g/cm^3), and bronze (8.60 g/cm^3) used in the matrix (Rahimian et al. 2009; Islak et al. 2012). Another reason is that the boron carbide melting point is higher than the other matrix materials and therefore affects the sintering process negatively (Islak et al. 2012). Figure 2 shows the effect of the boron carbide addition on the unit volume weight and the theoretical density.

Porosity

Porosity affects the mechanical properties of a material as well as corrosion and mechanical wear behavior due to the materials contained in the matrix (Fig. 3). In the study, porosity values of boron carbide-doped sockets were determined according to Eq. 1.

$$P = 100 - (UVW/TD * 100) \tag{1}$$

P porosity
UVW unit volume weight
TD theoretical density

Calculated porosity values are given in Table 3. It was observed that the boron carbide doped increased porosity.

The porosity ratio is increased because the bond between the boron carbide and the other matrix material interface is not stable due to the difference between the melting points. Figure 4 shows porosity change with respect to boron carbide contribution.

Hardness

During the rock cutting process, the matrix is exposed to fatigue because of variable loads. The most important task of the

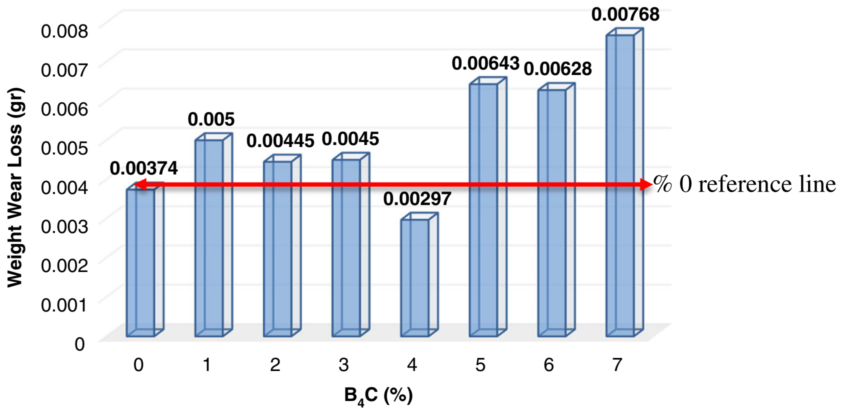
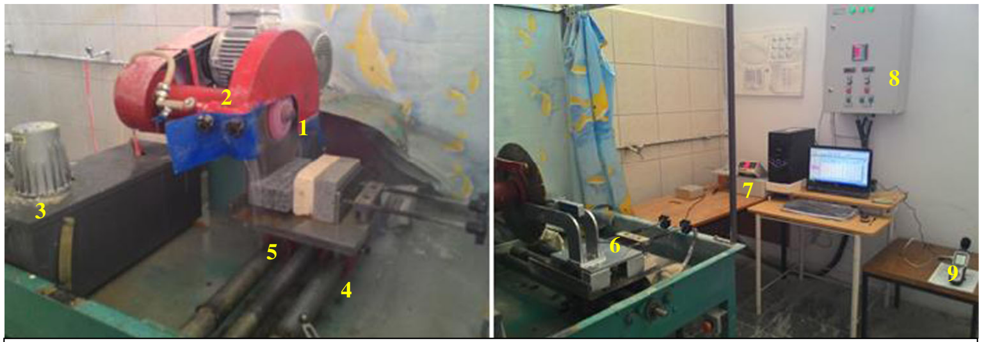


Fig. 9 Change in weight wear loss according to boron carbide doped

Fig. 10 General appearance of cutting test set elements



1. **Saw**
2. **Saw engine**
3. **Coolant pump**
4. **Carriage**
5. **Sample**
6. **Wear measurement system**
7. **Energy analyser**
8. **Electric panel**
9. **Noise meter**

matrix is to keep the diamond particles inside tightly. For this reason, the rigidity of the matrix has great precaution. Matrix hardness is largely dependent on the chemical composition of the used powder and its production parameters and in practice, hardness is regarded as a fundamental quality control parameter for sockets (Kır 2012).

In this study, Knoop hardness (HK) values were measured in the micro hardness measuring device of MITECH brand in Aha Evran University Kaman Vocational School's Rock Mechanics Laboratory in order to determine hardnesses of boron carbide-doped diamond sockets obtained by hot pressing (Fig. 5).

In the hardness measurements, three specimens of dimensions 3.2 × 10 × 40 mm were used for each boron carbide ratio. Measurements were made 50 times at frequent intervals from the surface of each sample and the whole socket surface was scanned. A total of 1200 hardness measurements were made and the averages were taken (see Table 4).

The highest hardness value was obtained in 4% boron carbide-doped sockets and the lowest hardness value was obtained in 6% boron carbide-doped sockets depending on porosity values. Figure 6 shows the change of Knoop hardness value according to boron carbide doped.

Weight wear loss

The purpose of using reinforcing elements in composite materials is to create hard phases within the soft structure. The hard phases increase both wear resistance and toughness (Özay and Hasçalık 2004). In the scope of the study, boron carbide-doped diamond sockets were produced at different rates by using hot pressing method in order to increase wear resistance of diamond sockets.

Table 6 Cutting parameters held constant in cutting experiments

Peripheral speed (Vç), m/sn	Cutting depth (hk), mm	Feed rates (Vi), m/dk
30	10	0.7

Weight abrasion tests were carried out by using the wear test set in the laboratory of Metallurgical and Materials Engineering Department of Fırat University (Fig. 7). In the wear tests, two samples were used from each group of diamond sockets. In the abrasion tests, the specimen was fixed primarily and then traveled 13 m with a load of 2 kg/cm^2 on diamond pin rotating at 30 rpm.

Surfaces were cleaned with alcohol before and after the surface abrasion test of the samples (Fig. 8). Dry weights of the samples were taken prior to the abrasion tests. As a result of the wear tests, the samples were reweighed to determine wear losses. Sensitive scales are used in the experiments. The obtained data are given in Table 5. Figure 9 shows the change in weight wear loss with respect to the boron carbide doped.

Table 7 Physical and mechanical properties of Hisar Gray rock

	Min	Avg	Max
SW	2.689	2.697	2.701
UVW (g/cm^3)	2.613	2.622	2.632
TP (%)	2.380	2.784	3.030
BSW (cm^3/50 cm^2)	7.601	7.640	7.677
UCS (MPa)	174.78	206.63	237.07
Is$_{(50)}$ (MPa)	7.10	7.97	9.36
BTS (MPa)	8.13	9.85	10.54
HK	315.65	445.82	622.12
SH	79.5	90.8	98.2

SW, specific weight; UVW, unit volume weight; TP, total porosity; UCS, uniaxial compressive strength; Is$_{(50)}$, point load strength index; BTS, Brazilian tensile strength; SH, Shore hardness; HK, Knoop hardness

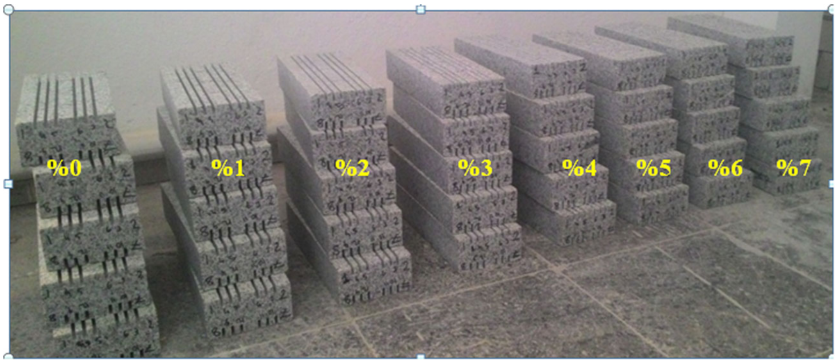


Fig. 11 View of block samples after cutting test

When the results obtained are examined, it is determined that 4% boron carbide-doped diamond sockets have the least mass loss due to high hardness. The highest weight wear loss value was obtained in 7% boron carbide-doped sockets due to low hardness and high porosity value. Figure 6 shows the weight wear loss change with respect to the boron carbide doped.

Cutting experiments

As a result of cutting experiments with boron carbide-doped and non-doped circular saws, net power consumption, and specific cutting energy that each saw consumed during cutting, noise values generated during cutting and specific wear values formed in sockets after cutting were determined.

Cutting experiments were carried out in cutting set in the Natural Stone Technology Laboratory of Mining Engineering Department of Süleyman Demirel University. Figure 10 gives an overview of the cutting test set elements.

Cutting performances of eight circular saws with boron carbide-free and doped (0-1-2-3-4-5-6-7 B4C) were determined in the study. Cutting parameters such as the peripheral speed of the saw, feed rates, cutting depth, and water volume were kept constant during cutting experiments. Cutting parameters are given in Table 6.

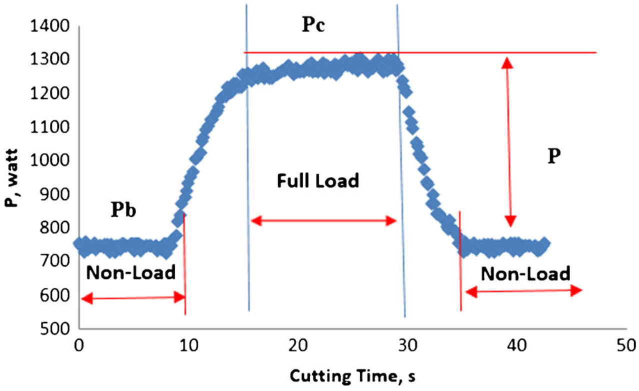


Fig. 12 Power-cutting time graph of 0% B_4C saw

A single natural stone type was used in the cutting experiments. Cutting experiments were carried out on Hisar Gray samples of 5 × 10 × 25 cm dimensions with a homogeneous structure. Physical and mechanical properties of Hisar Gray samples were determined before cutting experiments. The results are given in Table 7.

In the experiments, the downward cutting method widely used in the natural stone sector was chosen. Before the cutting experiments, abrasive concrete blocks were used to sharpen the saws. In the experiments, a constant amount of cooling water (10 l/min) was used with an external pump. In cutting experiments, 12 cuts were made on each block sample. For each saw, 60 cuts were made on 5 block samples. The appearance of block samples of dimensions 5 × 10 × 25 cm after the cutting experiments is given in Fig. 11.

Specific cutting energy

The specific cutting energy is defined as the amount of energy required to cut the rock in the unit volume and expressed in units of J/mm^3. The efficiency of the cutting depends on the maximum cutting speed and the minimum specific cutting energy. Providing these conditions is the most economical of the cutting process. For this reason, specific cutting energy is a criterion of cutting efficiency (Şengün 2009).

Table 8 Specific cutting energy values

%B_4C	SCE (J/mm^3)				
	Min	Avg	Max	Deviation	Cutting number
0	1.3469	1.4553	1.5153	0.051	60
1	0.8883	1.0493	1.2197	0.095	60
2	0.9895	1.0986	1.2575	0.081	60
3	1.0586	1.2632	1.4495	0.069	60
4	1.3945	1.4826	1.5498	0.076	60
5	1.0715	1.1896	1.2862	0.078	60
6	0.7449	0.9144	1.0477	0.075	60
7	0.7258	0.9044	1.0313	0.061	60

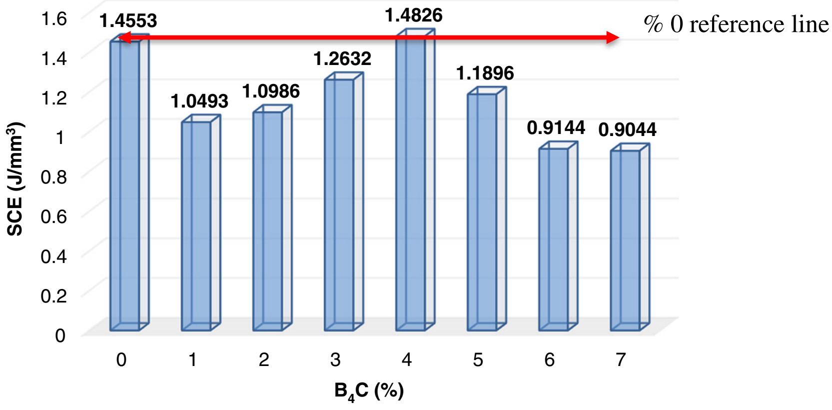


Fig. 13 Change of specific cutting energy values according to boron carbide additive ratio

In industrial applications, attention is paid to increasing the amount of production in the unit at a time, but the energy consumption for this process is ignored. However, the fact that the cutting process is economically feasible depends on providing the most production and less energy consumption per unit time (Büyüksağiş 1998).

In the study, first power consumption values were obtained to calculate the specific cutting energy values. Later, a power-time graph was drawn (Fig. 12). Using the graph, the power values the machine consumes during the unloaded operation and the power values that are consumed during full load are determined. The difference between these two values gives the net power value for the rock cutting (Eq. 2).

$$P = Pc{-}Pb \tag{2}$$

P	net power used for cutting, watts
Pc	power consumption in case of sawing, watt
Pb	power value of saw in non-load case, watt

The specific cutting energy values of the circular saws used in cutting tests are calculated using Eqs. 3–4. Power and specific cutting energy values during cutting were determined according to Şengün et al. (2009) study.

Table 9 Power consumption values

%B_4C	P (watt) Min	 Avg	 Max	 Deviation	Cutting number
0	642.72	707.85	760.93	28.87	60
1	429.70	529.32	618.96	57.14	60
2	511.72	561.86	677.82	50.09	60
3	481.62	570.81	651.79	53.60	60
4	675.24	720.85	785.93	48.25	60
5	575.64	636.28	713.81	37.05	60
6	386.38	452.22	522.77	36.55	60
7	368.72	430.26	480.07	33.52	60

$$FT = P/Vp \tag{3}$$

$$SCE = 0.06*(FT/Vp)/(h*Ws*Vi) \tag{4}$$

SCE	specific cutting energy, J/mm^3
FT	tangential force, N
Vp	peripheral speed, m/s
h	cutting depth, mm
Ws	socket width, m
Vi	feed rate, m/min

Parameters related to the rock properties cannot be changed in terms of cutting efficiency but it is possible to change parameters related to the cutting machine. In this study, the effect of boron carbide-doped circular saw on the specific cutting energy was investigated in fixed cutting parameters determined on a single granite type. The specific cutting energy values calculated after cutting tests are given in Table 8.

According to the obtained data, the highest specific cutting energy values were obtained in circular saw blades with 0% and 4% boron carbide-doped values. However, the 4% boron carbide-doped circular saw consumed 1.95% more energy than the 0% B_4C. As it is observed from the metallographic investigations, it was determined that porosity values of these two types of socket are close to each other and hardness value of 4% boron carbide-doped socket is higher than 0%. The lowest specific cutting energy value was obtained in a 7% boron carbide-doped circular saw. This is due to the fact that both the hardness and the porosity values of the saw are lower among the other circular saws. Therefore, it has a softer structure. Figure 13 shows the variation of specific cutting energy values according to the boron carbide additive ratio.

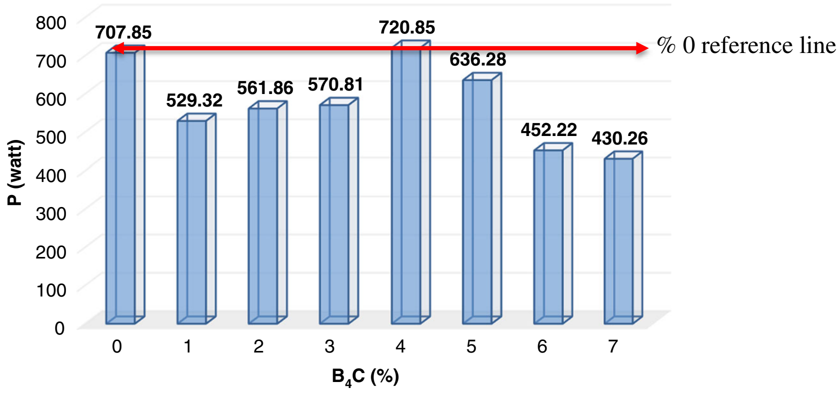


Fig. 14 Change of power consumption according to boron carbide additive ratio

Power consumption

In the natural stone sector, energy consumption constitutes an important cost item, especially in circular saw and granite production facilities. For this reason, determination of the power values used in cutting analyses is an important parameter in terms of cost and cutting efficiency. The power consumption values obtained as a result of the cutting tests are given in Table 9.

As a result, the highest consumption value was obtained in 4% and 0% B_4C saw. The lowest power consumption value was obtained in a circular saw with 7% boron carbide doped due to low hardness and high porosity value. It has been determined that a reduction of 39.22% in power consumption compared to 0% B_4C saws. The power consumption change values of the saws according to the boron carbide doped are given in Fig. 14.

Specific abrasion

Sockets used for natural stone cutting processes especially for the cutting of hard natural stones of granite type are abraded quickly and are consumed in a short time. Accordingly, an increase in production cost per square meter is an important problem. In natural stone cutting operations, the diamond and matrix must be worn optimally for the life of the cutting tool. For this reason, besides the type of diamond used in sockets, the choice of matrix is important.

In the scope of this study, a wear measurement system was established in order to determine diametrically abrasion in diamond sockets. MITUTOYO brand vertical linear measuring instrument which can measure 25 mm with 1 μm accuracy and MITUTOYO brand digital signal converter which makes numerical data from vertical linear measuring instrument and SENSORPAK software which transfers the measurements made to the computer are available in the created system. With this software, wear measurements have been performed over a period of 2 ms.

Before the cutting tests, the abrasion measuring instrument is placed at the point determined on the wagon in the cutting test set. Measurement is carried out by placing the linear measuring instrument on the reference line (see Fig. 15).

The same procedures were repeated after the cutting tests. The amount of decrease in diamond socket height was determined by taking the difference between the first and last measurements. Specific abrasion values ($\mu c/m^2$) were determined by the ratio of worn height difference to cutting area. The specific abrasion values obtained are given in Table 10.

The highest hardness value is obtained depending on the suitably condensed matrix-diamond mixture and matrix composition. On the other hand, if the structure of the socket is damaged in any direction or if the condensation cannot be completed, sufficient hardness value cannot be obtained. As

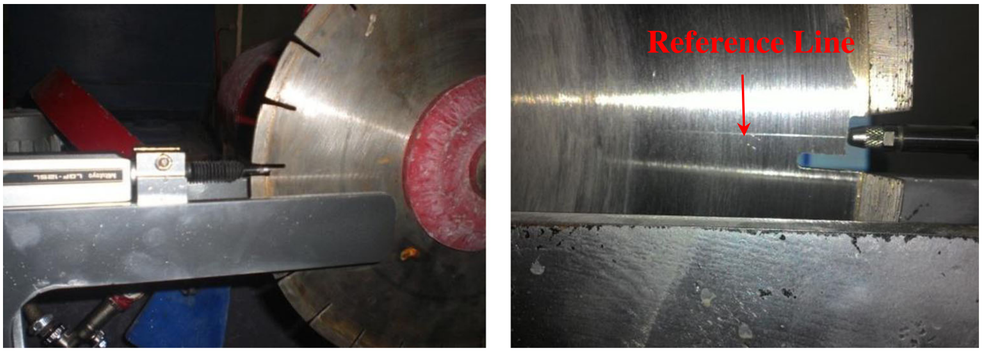


Fig. 15 Wear measurement system and reference point on the saw

Table 10 Specific abrasion values

%B_4C	Specific abrasion values (μc/m^2)
0	90.34
1	100.15
2	98.98
3	93.73
4	84.84
5	109.70
6	115.41
7	128.52

Table 11 Noise values

%B_4C	Noise values (dB(c))				
	Min	Avg	Max	Deviation	Cutting number
0	96.33	96.98	97.79	0.31	60
1	91.53	92.81	93.66	0.71	60
2	92.17	93.02	93.74	0.21	60
3	92.85	93.96	94.70	0.41	60
4	95.75	96.25	96.99	0.34	60
5	95.28	95.65	95.96	0.29	60
6	94.32	94.98	96.51	0.53	60
7	93.05	93.69	95.55	0.50	60

a result, matrix abrasion resistance is low and matrix diamond holding ability is poor (Çelik 2009). In the study, the highest hardness value of 4% B_4C was also obtained. The abrasion of the matrix surface is reduced due to the increase in hardness. Due to its high hardness, the lowest specific abrasion value was achieved at a 4% B_4C doped. In addition, 4% B_4C-doped diamond sockets are worn down by 6.08% less than 0% B_4C diamond sockets and saw life is increased. The highest wear value was obtained in the ratio of 7% B_4C doped, which is the highest porosity. The change in specific abrasion values according to the boron carbide additive ratio is given in Fig. 16.

Noise level

Today, one of the most common occupational diseases is hearing loss caused by excessive noise. For this reason, marble processing plants are making efforts to reduce the noise level, especially when continuous disk type cutters are used. Legal practice obliges workers to work on low-noise machines and use noise reduction tools.

As a result of the forces applied by the saw to the stone, the shock waves generated by the vibrations between the saw and the rock are transmitted as noise in the air. The resulting noise depends on saw design (steel properties, blade thickness, saw blade diameter, socket geometry and number, width between water channels), rock properties (hardness, mineralogical properties, etc.), and operating parameters (cutting speed, feed rate, cutting depth, peripheral speed, and amount of cooling water) (Yılmaz 2009).

In this study, noise values of boron carbide-doped circular saws during cutting were determined. During the measurements, the distance between the cutting test set and the noise meter was fixed at 2 m. The noise levels are measured in the dB (c) band, which is sensitive to machine noise. The obtained data are given in Table 11.

The highest noise values were found to be close to each other with 0% B_4C and 4% B_4C-doped diamond sockets. The porosity values of the sockets were increased due to the increase in boron carbide-doped rate. The socket hardness decreased with the increase of porosity values. Accordingly, the socket wear values increased. Due to the increase in wear values, new diamond grains have reached the surface of the socket and facilitated the cutting process. In this case, the noise values decreased. The lowest value was obtained in 1% B_4C-doped sockets and it was determined that noise reduction by 4.30% compared to 0% B_4C sockets. Figure 17 shows the change of noise values according to the ratio of boron carbide doped.

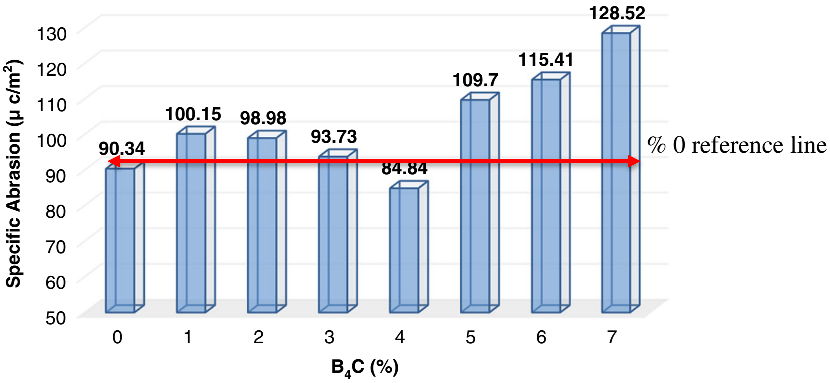


Fig. 16 Change of specific abrasion values according to boron carbide doped

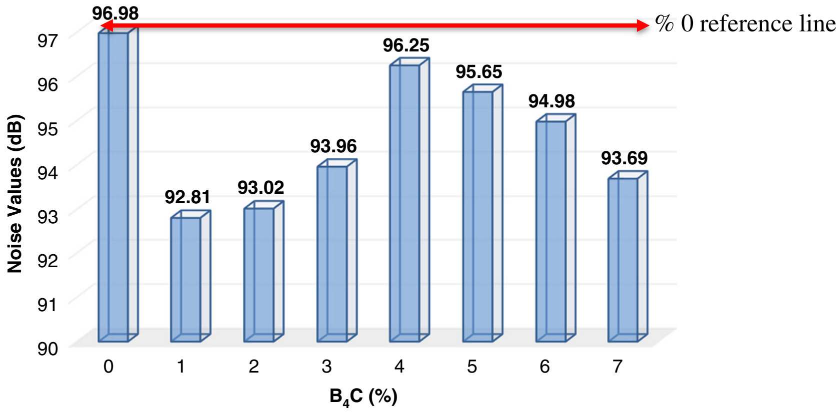


Fig. 17 Change of noise values according to boron carbide-doped ratio

Results and discussion

In this study, it is aimed to increase resistance against wear of diamond socket by boron carbide doped for matrix composition of diamond sockets used for natural stone cutting. Besides, cutting parameters such as power consumption, specific cutting energy, and noise values of boron carbide-doped circular saws are determined and cutting performances of circular saws with boron carbide doped have been demonstrated.

The results obtained from the study are summarized below.

- As a result of increasing the amount of boron carbide, it is determined that the weight of unit volume decreases. This is due to the low boron carbide density (2.52 g/cm^3) compared to the cobalt (8.90 g/cm^3), nickel (8.85 g/cm^3), and bronze (8.60 g/cm^3) used in the matrix (Rahimian et al. 2009; Islak et al. 2012).
- Boron carbide doped has been observed to increase porosity. The reason for this is thought to be due to the fact that bonding at the interface of boron carbide and other matrix materials is not robust due to the difference between the melting points.
- As a result of wear tests, it has been determined that 4% boron carbide-doped diamond sockets have the highest resistance against wear due to their high hardness value.
- According to the obtained data, the highest specific cutting energy values were obtained in circular saw blades with 0% and 4% boron carbide-doped values. However, the 4% boron carbide-doped circular saw consumed 1.95% more energy than the 0% B_4C. As it is observed from the metallographic investigations, it was determined that porosity values of these two types of socket are close to each other and hardness value of 4% boron carbide-doped socket is higher than 0%. The lowest specific cutting energy value was obtained in a 7% boron carbide-doped saw. This is due to the fact that both the hardness and the porosity values of the saw are lower among the other saws.
- After cutting tests, specific abrasion values were determined in μm/m^2. The lowest specific abrasion value was obtained at a ratio of 4% B_4C doped since the fracture of the matrix surface decreased with increasing hardness. Four percent B_4C sockets are less than 6.0% less than 0% B_4C sockets and saw life is increased. The highest abrasion value was obtained in 7% boron carbide-doped ratio.
- Considering the lowest noise level, 1% B_4C-doped circular sawing is considered to be beneficial to the natural stone sector when it is taken into account in terms of worker health and safety.

In this study, it was determined that boron carbide can be used for cutting tool matrix. In future works, performances of 0.5-1.5-2.5% boron carbide-doped saw blades produced under appropriate sintering conditions should be determined at different cutting conditions (different cutting speeds, at different peripheral speeds). It is also thought that it is more accurate to determine the optimum boron carbide ratio considering the production costs of boron carbide-doped sockets.

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References

Alp E, Karaçay E, Cabbar HC (2013) Low temperature production of boron carbide and its characterization, vol 28. Gazi Uni. Faculty of Engineering and Architecture Magazine, pp 293–302

ASTM Standard B 311-08 (2009) Standard test method for density of powder metallurgy (Pm) materials containing less than two percent porosity. ASTM International, West Conshohocken

Atıcı Ü (2005) The factors effected of rock cutability. Ph.D. thesis, Çukurova Uni., Adana, 180p

Büyüksağiş IS (1998) Analysis of sawability of marbles with diamond disc block cutter machines. Ph.D. thesis, Osmangazi Uni. Eskişehir, 172p

Büyüksağiş IS (2007) Effect of cutting mode on the sawability of granites using segmented circular diamond sawblade. J Mater Process Technol 183:399–406

Büyüksağiş IS, Goktan RM (2005) Investigation of marble machining performance using an instrumented block-cutter. J Mater Process Technol 169:258–262

Çelik E (2009) Alternative binders of diamond cutting tools. Ph.D. thesis Fırat Uni. pp. 91, Elazığ

Ekincioğlu G (2017) Investigation of the effects on cutability parameters of boron carbide doped diamond sockets in natural stone cutting process. Ph.D. thesis, Süleyman Demirel Uni. Isparta, 157p

Ersoy A, Atıcı U (1999) Wear mechanisms of marble cutter. The 16th mining congress of Turkey, pp 107–115

Eyuboglu AS, Ozcelik Y, Kulaksiz S, Engin IC (2003) Statistical and microscopic investigation of disc segment wear related to sawing Ankara andesites. Intl J Rock Mech Min Sci 40:405–414

Güneş Yılmaz N (2013) Process efficiency comparison of a sandwich-core sawblade and a conventional sawblade used in stone-machining. J Clean Prod 47:26–31

Güneş Yılmaz N, Göktan MR (2008) Effect of sawing rate on force and energy requirements in the circular sawing of granites. Journal of Engineering and Architecture of Eskişehir Osmangazi Unı XXI 2

Hwang KS, Yang TH, Hu SC (2005) Diamond cutting tools with a Ni_3Al matrix processed by reaction pseudo-hipping, vol 36A. Metallurgical and Materials Transactions

Islak S, Kır D, Çelik H, Çelik E (2012) Effect of boron carbide on the microstructure and the mechanical properties of segments produced using hot pressing method. Sci Res Essays 7(23):2095–2103

Karaçay E (2008) Production of boron carbide and its characterization. M.Sc. Thesis, Gazi Uni. Ankara, 118p

Karakuş A (1999) Examination of sawability parameters of quarrible marbles in Diyarbakir Region. M.Sc. Thesis, Çukurova Uni. Adana, 79p

Kır D (2012) Investigation of use of cubic boron nitride (CBN) as alternative abrasive in natural stone cutting tools. Ph.D. thesis, Fırat Uni., pp.107, Elazığ

Li Y, Huang H, Shen JY, Xu XP, Gao YS (2002) Cost-effective machining of granite by reducing tribological interactions. J Mater Process Technol 129:389–394

Luo SY, Liao YS (1995) Study of the behaviour of diamond saw-blades in stone processing. J Mater Process Technol 51:296–308

Ma QC, Zhang GJ, Kan YM, Xia YB, Wang PL (2010) Effect of addives introduced by ball milling on sintering behavior and mechanical properties of hot-pressed B_4C ceramics. Ceram Int 36:167–171

Öksüz KE, Şimşir M, Şahin Y (2011) Investigation of B_4C additions to cutting tips produced by powder metallurgy and used for cutting marble, vol 6. International Powder Metallurgy Conference and Exhibition, pp 588–591

Özay Ç, Hasçalık A (2004) Effect of C ratio on abrasive wear resistance in Cu-C-Al2SiO5 composite produced by P/M method. Journal of Science and Technology of Dumlupınar University 6:175–184

Özçelik Y, Ünver B, Bayram F, Yaşıtlı NE (2008) Sawability classification of some natural stones with circular sawing and numerical modelling of sawing mechanism. TÜBİTAK, Turkey

Özel S, Çelik E, Turhan H (2009) The investigation of microstructure and mechanical properties of Cu-Al/B_4C composıtes produced by usıng Hot Pres. E-Journal of New World Sciences Academy 4(1)

Pierson HO (1996) Handbook of refractory carbides and nitrides. William Andrew pub. Noyes

Polini W, Turchetta S (2005) Evaluation of diamond tool wear. Int J Adv Manuf Technol 26:959–964

Rahimian M, Ehsani N, Parvin N, Baharvandi HR (2009) The effect of particle size, sintering temperature and sintering time on the properties of Al–Al_2O_3 composites. Made by powder metallurgy. J Mater Process Technol 209:5387–5393

Şengün, N (2009) The effects of fracture toughness and brittleness of rocks on sawing efficiency with circular discs. Ph.D. thesis, Süleyman Demirel Uni., pp.165, Isparta,

Şengün N, Altındağ R, Koçcaz CE (2009) The sawability analysis of some magmatic rocks in Isparta region. DEÜ Uni. J Sci Eng 11: 23–31

Şengün N, Altındağ R, Demirdağ S, Koççaz C E (2010) Assessment of noise pollution in marble processing plants in terms of worker health and related legislation. İTÜ 12. Industrial Pollution Control Symposium, 427–432, Istanbul

Şengün N, Altındağ R, Demirdağ S (2013) Investigation of saw rotation count and noise level changes in circular saw cutting process. Pamukkale University Journal of Engineering Sciences 19:121–121

Xu X (1999) Friction studies on the process in circular sawing of granites. Tribol Lett 7:221–227

Xu X, Yu Y (2005) Sawing performance of diamond with alloy coatings. Surf Coat Technol 198:459–463

Xu XP, Li Y, Zeng WY, Li LB (2002) Quantitative analysis of the loads acting on the abrasive grits in the diamond sawing of granites. J Mater Process Technol 129:50–55

Yılmaz N (2009) Sawability analyses of magmatic-origin natural stones using diamond segmented saws. Ph.D. thesis, Eskişehir Osmangazi Uni., pp. 209, Eskişehir,

Yurdakul M, Akdaş H (2012) Prediction of specific cutting energy for large diameter circular saws during natural stone cutting. Int J Rock Mech Min Sci 53:38–44