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Effect of Diamond Grain Sizes on Cutting Forces and Specific Energy in Marble Milling Processes

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Mermer Frezeleme İşlemlerinde Elmas Tane Boyutlarının Kesme Kuvvetlerine ve Özgül Enerjiye Etkisi

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Abstract

In this study, the effects of diamond grain size on cutting forces and specific energy parameters were investigated using vacuum brazed coated milling tools (T_{301}, T_{405}, T_{602}) for milling marbles with different structural properties. Marbles, as natural building materials, are typically difficult to machine due to their different physical and mechanical properties. Bursa White marble with fine mineral grains with granoblastic texture and Muğla White marble with coarse mineral grains with crystalline texture were used in the experiments. Diamond coated milling tools produced by the newly developed vacuum brazing technology were used. In milling operations, 6000-10000-12000 rpm cutting speed, 1500-2250-3000 mm/min feed rate parameters were applied. The effects of diamond grain sizes were analyzed by investigating the Fz (N) value, cutting force Fc (N) value and specific energy values acting in the perpendicular direction during milling. As a result, T_{602} diamond tools showed better cutting performance than other tools. In the processing parameters, good results were obtained at 12000 rpm and 3000 mm/min feed rate. Muğla White marble has approximately 52% higher shear force and 77% higher specific energy value than Bursa White marble. It was determined that the structural properties of marbles have an effect on cutting performance.

Öz

Bu çalışmada, farklı yapısal özelliklere sahip mermerlerin frezelemesinde vakumlu lehimleme yöntemiyle kaplanmış freze takımlar (T_{301}, T_{405}, T_{602}) kullanılarak elmas tane boyutunun kesme kuvvetleri ve spesifik enerji parametrelerine olan etkileri araştırılmıştır. Mermerler, doğal yapı malzemesi olarak farklı fiziksel ve mekanik özelliklerinden dolayı tipik olarak işlenmesi zor malzemelerdir. Deneylerde granoblastik dokuya sahip ince mineral taneli Bursa Beyaz mermer, kristalin dokuya sahip iri mineral taneli Muğla Beyaz mermer kullanılmıştır. Yeni geliştirilmiş olan vakumlu lehimleme teknolojisi ile üretilen elmas kaplamalı freze takımlar kullanılmıştır. Frezeleme işlemlerinde 6000-9000-12000 rpm kesme devri, 1500-2250-3000 mm/min ilerleme hızı parametreleri uygulandı. Frezeleme süresince Dik yönde etki eden Fz (N) değeri, kesme kuvveti Fc (N) değeri ve özgül enerji değerleri araştırılarak elmas tane boyutlarının etkileri incelenmiştir. Sonuç olarak T_{602} elmas takımların diğer takımlara göre daha iyi kesme performansı göstermiştir. İşleme parmetrelerinde ise 12000 dev/dk ve 3000 mm/dk ilerleme hızında iyi sonuçlar alınmıştır. Muğla Beyaz mermerin Bursa Beyaz mermere göre yaklaşık %52 kesme kuvveti ve %77 spesifik enerji değeri daha fazla olmuştur. Mermerlerin yapısal özelliklerinin kesme performansı üzerinde etkili olduğu tespit edilmiştir.

Anahtar Kelimeler: *Marble; spesific energy, cutting force, grain size.*

Keywords: *Mermer; özgül enerji, kesme kuvvetleri, tane büyüklüğü*

1. Introduction

Natural stones have a long history in human history as architectural, artistic and building materials. Natural stones have played a significant role not only as building materials but also in sculpture and art. With CNC milling machines, different product designs can be made with various processes such as carving, embossing, relief, cutting and writing of natural stones, thus diversifying the usage areas of natural stone. Marbles as natural stone are widely used in CNC milling processes as they are frequently preferred in architecture, interior design, sculpture and many other applications due to their aesthetic appeal, durability and various color and pattern options (Özkan and Öz 2023, Özkan et al. 2023).

Metal materials are generally hard, durable and corrosive materials. They are widely used in industries such as automotive, construction, electronics and aerospace. They are easy to machine and shape with CNC. Metal milling machines are usually equipped with motors with higher rotational speeds and higher torques. Tungsten carbide high-speed steel cutters (HSS) and ceramic inserts and a wide variety of coatings such as TiN (Titanium Nitride), TiCN (Titanium Carbonitride), TiAlN (Titanium Aluminum Nitride), AlTiN (Aluminum Titanium Nitride), DLC (Diamond-Like Carbon) are commonly used as tool coatings. During machining, temperature control is important, cooling systems such as liquid, air and lubrication, and chip removal systems are needed.

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Because the temperature increases during machining when working with hard and resistant materials, it is very important to control the temperature and remove the chips. Since it is a ductile material, a long and continuous chip strip is formed during milling in soft metals, while a brittle chip is usually formed in hard metals. Machining parameters such as cutting speed, feed rate and depth of cut affect the size of the chips (Altıntas 2012, Chattopadhyay 2017, Haynes 2015). Natural stones are heavy, durable and aesthetically diverse materials. They are used in interior and exterior architecture, sculpture, and floor coverings. Natural stones are generally hard and brittle materials, so CNC milling machines are specially designed to take into account the hardness and brittleness of natural stone. CNC milling machines must have powerful motors and high torque, and must also have a machine structure that is resistant to vibrations that may occur during processing. For the reasons mentioned, cutting tools, cutting mechanics and all other processing parameters differ.

Wang et al. (2020) investigated the wear of diamond segments when cutting hard stones in different saw cutting modes. They used two types of saw cutting modes. The wear effects of trajectory and diamond segments were investigated. It was found that in the reciprocating sawing mode and when using cobalt-based segments, the cutting length and cutting time were shortened while the matrix was worn more slowly. Li et al. (2018) applied PNMM to investigate the drawing of rock material considering its dynamic behavior. With increasing cutting speed, MSE and cutting force also increased, the actual depth of cut was defined and found to increase with increasing rake angle. Turchetta and Polini (2011) tried to develop an empirical model to relate cutting parameters to force and energy values in milling operations of Coreno Perlato Royal stone. A simple linear relationship was used to model the metal removal rate, force and energy values. Lu et al. (2020) investigated tool wear in cutting white marble with a multilayer diamond-coated tool and studied the wear condition and failure mechanism of the tool. Abbassi et al. (2021) aimed to find the optimum cutting parameter to minimize the cylindricity and surface roughness of the holes using rotational speed in milling Calacatta-Carrara white marble. The optimization process was carried out using the Gray Relational Analysis (GRA) technique with minimum tolerances of cylindricity and roughness. Yan et al. (2021) aimed to optimize the parameters for milling zirconia ceramics with a polycrystalline diamond tool. For this purpose, they simulated a machining process based on the Johnson-Cook structural model using the finite element method. The research investigated the effects of spindle speed, feed rate, radial and axial cutting depth on cutting force, tool flank wear, and material removal rate. The optimal parameter combination was found to be a spindle speed of 8000 rpm, a feed rate of 90.65 mm/min, a radial cutting depth of 0.10 mm, and an axial cutting depth of 1.37 mm. Balasubramanyam and Chittappa (2021) investigated the effects of cutting forces on the saw blade during deep sawing of granite to finite length. In order to compare the wear of two cutting wheels from different manufacturers, the wear of the diamond segment was compared when sawing granite with a circular saw. Ternero et al. (2021) investigated the wear of two sintering motors using five types of granite and marble with 15 different metallic binders at three different contact forces. They investigated the relationship between wear and mechanical properties of binders. Wang et al. (2021) investigated the mechanical interaction between rock and diamond particles. They studied the chip geometry model to investigate the relationship between diameter, depth, chip arc length and thickness. They found that the wear differences of diamond particles on the segment were caused by the difference in chip thickness and contact length; the wear values of small-diameter saw blade were higher than those of large-diameter saw blade. Sun et al. (2022) investigated the morphological characterization and wear behaviour of diamond grains in cutting granite with a circular saw by studying the crystal plane properties of diamonds. Abrasive wear and surface fatigue wear were found to be the main factors in the wear of diamond grains. Wu et al. (2023) investigated the cutting mechanism (chip formation and morphology, cutting force, temperature and surface roughness) of stone-plastic composite in vertical cutting experiments by finite element simulations. The depth of cut is directly proportional to the cutting force and surface roughness, while the cutting force is inversely proportional to heat generation. They concluded that surface roughness is directly proportional to rake angle and depth of cut and inversely proportional to cutting speed. Aslantas et al. (2009) investigated the effect of axial forces on the cutting performance of circular saws used in the marble cutting process. In addition to normal and tangential forces, the effects of axial forces on the economic life of the cutting disc and segment wear were also considered. Experimental results show that increasing the feed rate and depth of cut significantly increases the axial deflection of the cutting disc. Yin et al. (2023) In order to predict the machining error and milling depth during the machining of marble workpiece, a spherical hardness model of stone carving robotic manipulators (SCRM) was established and the relationship between milling force and milling depth was investigated. An error compensation method for stone milling based on robot kinematics is established. Cserta and Gyurika (2021) investigated the effects of granite minerals on the surface roughness of three different granite samples at different cutting speeds. Although the three samples could not be evaluated together due to their different physicochemical properties, it was concluded that biotite minerals had the lowest surface roughness and 154ort h minerals had the highest surface roughness at the same cutting speed. Polini and Corrado (2021) An attempt was made to develop a digital twin to manage force, energy and tool wear in ornamental stone machining. Widely tested high quality models were used for simulation by cutting with diamond milling cutters and disk saws, taking into account the parameters of chip thickness, depth of cut and feed rate. There is a continuous and clear flow of information from the machine tool to the tool, from cutting force and energy estimation to tool wear prediction. Good agreement between virtual and experimental results was found. Wu et al. (2022) established a model of the average chip thickness in granite cutting. The wear mechanism of diamond segments with cutting forces, the width of the saw kerf and the wear morphology of diamond segments were analyzed. The average wear rate of the segments increases with the feed rate and the average diamond exposure is low due to the large load during granite cutting. The width of the saw kerf is gradually reduced during the sawing process, forming a cone with a wide top and narrow bottom. It was also found that the clearance of the saw kerf increases as the feed rate increases during cutting. Wan et al. (2023) investigated the cutting tool structure and performance affecting the cutting performance of carbon fiber reinforced silicon carbide matrix (Cf/SiC) composites in milling. In the research, a polycrystalline diamond (PCD) tool designed with small micro-grooves on the edges was used and its geometrical parameters were optimized by finite element simulation. The results showed that the designed tool exhibited better cutting performance than the conventional straight-edged PCD tool. Song et al. (2023) investigated the cutting performance and wear behavior of Cf/SiC composites during milling process using different tools. The hard particles and protruding fiber wires formed during the milling process cause wear of diamond grains from PCD tools. Taking the spiral milling cutter of Qiao et al. (2022) as a reference, the temperature field of RCF milling cutter with single diamond coating produced by HFCVD setup was precisely simulated and analyzed using the finite volume method (FVM). As a result, it was found that the grain size and thickness uniformity of diamond coatings under optimized HFCVD setup parameters were significantly improved at different positions in the axial direction, which demonstrated the effectiveness of simulation as an optimization method.

In this study, various studies have been carried out on different types of stones with carbide or electroplated tools. Milling operations are performed using tungsten carbide coated, electroplated diamond tools that can withstand the hard structure of natural stone and there is no other alternative tool. Vacuum brazed diamond milling tools produced by a new method in Turkey will be used and studies to determine the cutting performance of this tool will be carried out for the first time. The effects on the durability, cutting accuracy and overall performance of the newly manufactured tools in milling operations of marbles will be investigated to ensure that the cuts are more accurate and in accordance with the desired dimensions and to better understand the cutting mechanism.

3. Test Process

3.1 Machinery and Experimental Design

In this study, an industrial natural stone milling machine (MEGASTONE 2030 4 AXIS MULTIFUNCTIONAL), which is widely used in practice, was used for milling operations at Afyon Kocatepe University, Department of Mining Engineering Laboratory. Real marbles of metamorphic origin extracted from marble quarries in Bursa and Muğla provinces were used in the experimental studies. The properties of the stones are listed in Table 1.

Table 1. Physico-mechanical properties

	P (%)	D (kg/m³)	WA (%)	CS (Mpa)	FS (Mpa)	AV (mm)
Bursa White Marble	0.5	2823	0.1	80	13.1	19.1
Muğla White Marble	0.6	2871	0.1	106	9.0	18.2

P: Porosity (EN 1936), D: Density (EN 1936), WA: Water Absorption (EN 13755), CS: Compressive Strength (EN 1926), FS: Flexural Strength (EN 13161), AV: Abrasion Value (EN 14157).

The mineralogical composition of the samples was examined by electron microscope (NIKON ECLIPSE 2V100POL). Bursa Marble has medium to coarse mineral grain size and Muğla Marble has fine to medium mineral grain size. Thin section images are given in Figure 1. The chemical structure of the samples was analyzed by XRF (X-ray fluorescence). It contains CaO compounds ranging between 98-100%. Characteristic properties of the stones are given in Table 2.

Table 2. Characteristic features

Sample	**Code**	**Photo**	**Mineral Distribution**	**Texture**	**Particle Width (µm)**		
					Minimum	***Maximum***	***Average***
Bursa White	B		% 98.94 Calcite	Granoblastic	5.5	1002.1	123.0
Muğla White	M		% 98.38 Calcite	Crystalline	33.1	2159.3	475.2

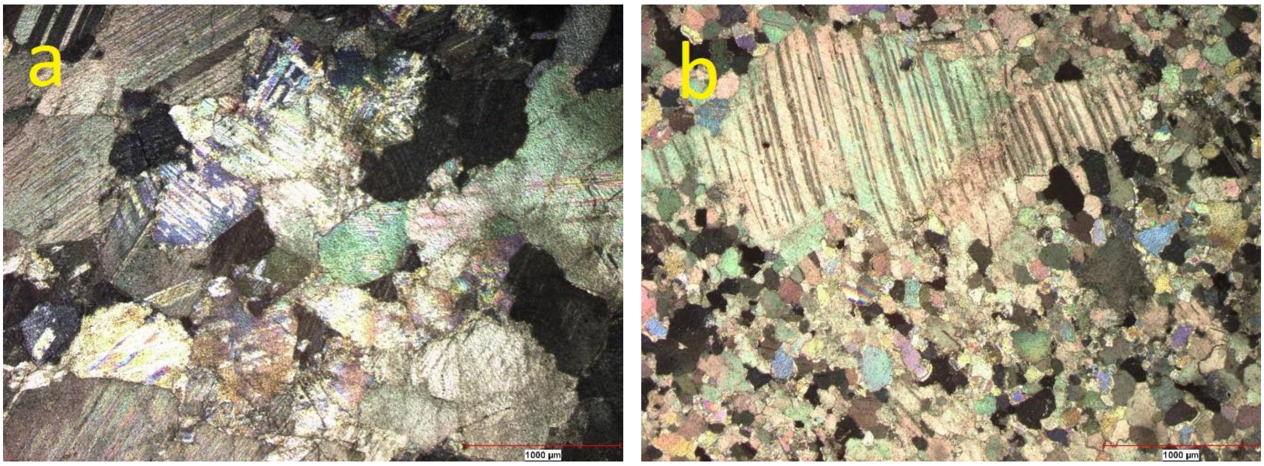

Figure 1. Mineralogical section images (a: Muğla White marble, b: Bursa White marble)

Three different tools with vacuum brazed diamond grain widths of 30/40 mesh (T_{301}), 40/50 mesh (T_{405}) and 50/60 mesh (T_{602}) were used in the milling tests. The diamond cutting tools will be referred to as T_{301}, T_{405}, T_{602} respectively according to their diamond grain size. The cutting tool has a diameter of 6 mm and 20 mm of the tool with a total length of 60 mm is diamond coated (Figure 2). Diamond cutting tools will be referred to as T_{301}, T_{405}, T_{602} respectively according to their diamond grain size.

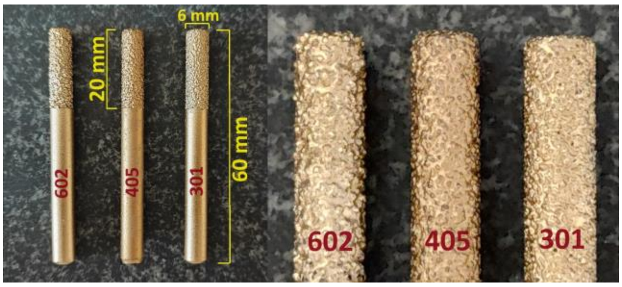

Figure 2. Vacuum diamond milling tools

The load meter test devices (ESIT BS model dynanometer) on the CNC vertical machining machine were used to measure the energy (watts) (Hioki power analyzer) and cutting force (N) (Fx, Fy, Fz) (Defne lab. soft software) with a precision of 100 ms. Figure 3 shows the experimental flow.

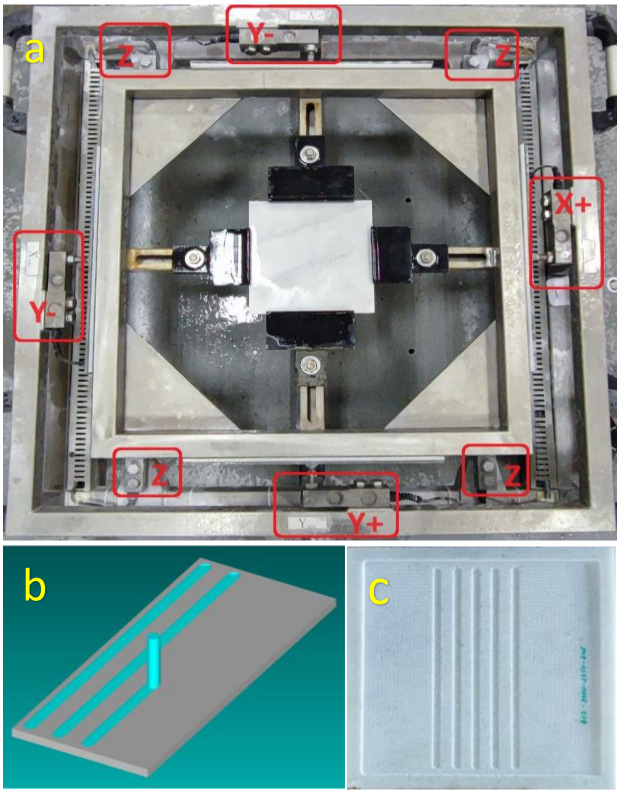

Figure 3. a) Milling force measurement table (X, Y and Z axis force dynamometers are marked on the picture), b) Modeling with AlphaCAM, c) Surface image after milling.

For the milling process, experiments were carried out at 6000rpm-1500mm/min, 9000rpm-2250 mm/min, 12000rpm-3000 mm/min (Parameters will be expressed as V1, V2 and V3, respectively) with reference to our previous studies. The cutting condition was wet cutting. Full cutting was performed with the cutting tool. Samples with dimensions of 200x200x20 mm were used. The machining parameters are listed in Table 3.

Table 3. Parameters

Spindle Cycle (rpm)	Feed Rate (min/mm)	Axial depth of cut a_p (mm)	Radial depth of cut a_e (mm)	Milling type
6000	1500			
9000	2250	1	6	Wet
12000	3000			

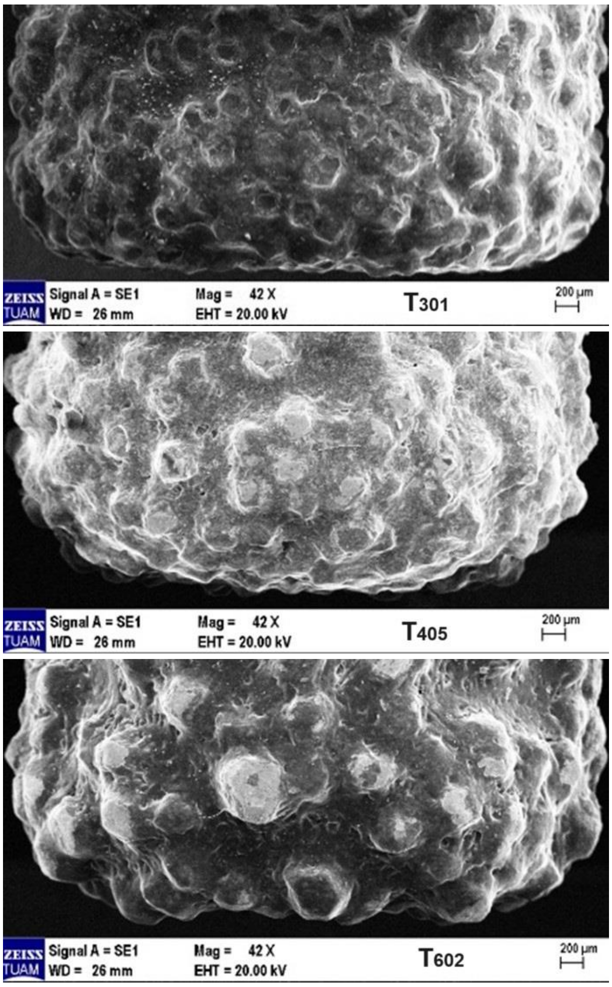

Figure 4. SEM Images of T_{301}, T_{405}, T_{602} diamond tools.

The surface of the samples was leveled to eliminate the thickness differences that occurred during sizing in marble factories. To ensure measurement accuracy, the surface quality of all samples was brought to the same condition. Separate cutting tools were used for leveling operations. Milling is an interrupted machining process in which a high-frequency dynamic load is applied to the cutting tool. The interaction between cutting tool and material affects the quality of the final product (Li et al. 2020). Changes in milling machinability with diamond tools coated with different grain widths at high and low cutting parameters were investigated. The effectiveness and relationship of the interaction between diamond grain size and stone on cutting forces and specific energy were investigated.

5. Results

The cross-sectional topographies of the vacuum diamond coatings (T301, T405 and T602 µm respectively) were observed by scanning electron microscopy (SEM) shown in Figure 4. The hard and abrasive nature of diamonds increases the size of the cut on the material surface of the material being machined by cutting tools and affects the cutting forces. Table 5 shows the specific cutting energy, cutting force and vertical force (Fz) applied during cutting.

Table 5. Results table.

Cutting Parameters	Diamond Code	Marble Code	Fz (N)	SE (J/cm^3)	Fc (N)
6000 rpm – 1500 mm/min	T_{602}	M	31.61	472.24	4.62
	T_{405}	M	42.32	539.98	3.10
	T_{301}	M	43.38	744.23	8.33
	T_{602}	B	29.96	368.03	3.77
	T_{405}	B	46.54	527.96	2.97
	T_{301}	B	44.46	417.26	3.20
9000 rpm – 2250 mm/min	T_{602}	M	59.01	623.70	2.78
	T_{405}	M	41.96	746.09	3.74
	T_{301}	M	35.87	521.41	3.97
	T_{602}	B	46.84	548.23	3.21
	T_{405}	B	46.22	492.07	3.22
	T_{301}	B	30.89	456.00	2.66
12000 rpm – 3000 mm/min	T_{602}	M	28.00	396.57	2.57
	T_{405}	M	40.72	578.41	4.28
	T_{301}	M	45.12	506.55	4.66
	T_{602}	B	28.98	224.17	1.68
	T_{405}	B	34.47	462.87	3.20
	T_{301}	B	43.37	533.81	4.02

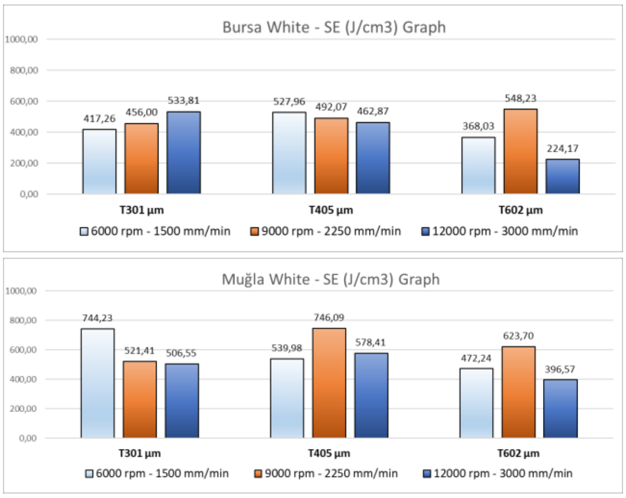

Figure 5. Spesific energy graphs

Specific energy consumption values of the milling process of Muğla white (M) and Bursa white (B) marbles according to cutting parameters and diamond grain sizes are shown in Figure 5. There are differences in the specific energy consumption of M and B due to their crystalline and granoblastic texture, respectively. The average calcite grain size of M is approximately 4 times higher than B. The size and shape of calcite grains, internal arrangement of grains and bonding between grains are different in M and B rocks. The lowest SE values for M and B were found at T602 tool and V3 cutting parameter. We can also say that the SE value of B rock is approximately 77% easier to cut than M rock.

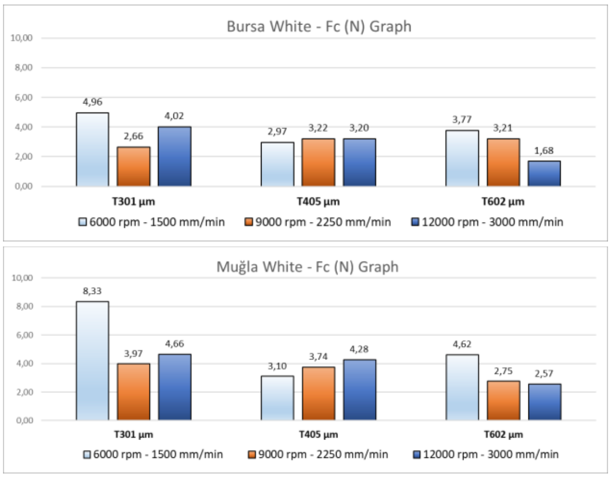

Figure 6. Fc (N) force value graphs

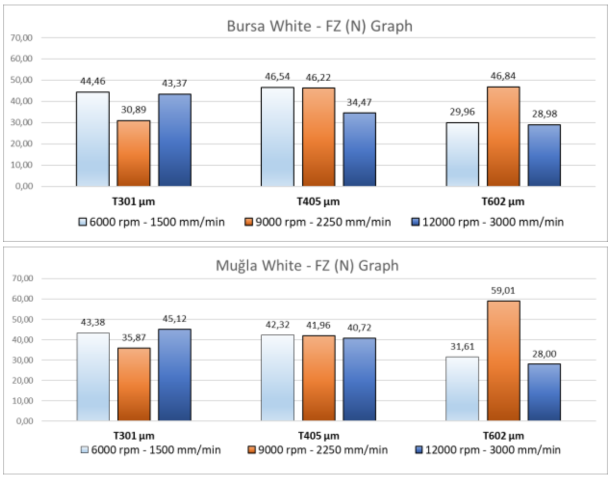

Figure 7. FZ (N) force value graphs.

Cutting force (Fc) values for M and B marbles according to cutting parameters and diamond grain sizes are shown in Figure 6 and force applied in vertical direction (FZ) values are shown in Figure 7. The lowest values for Fc and FZ forces were at T602 and V3 speeds. The size of the diamonds, the textural composition of the calcite mineral grains and the mineral distribution vary on the machining surface. This difference caused variations in the forces exerted by the diamonds in the contact zone according to the processing parameters.

While coarse-grained M calcite grain shapes show a more proportional and homogeneous distribution, fine-grained B shows a disproportionate and heterogeneous distribution with very fine grains distributed between the grains. This is more clearly seen in the thin section images in Figure 1. In addition, M has a crystalline texture and calcite grain boundaries are prominent. B, on the other hand, has a granoblastic texture and it is seen that the grains are intricately interlocked with each other. These microstructural differences caused differences in the cutting mechanics in the contact zone between the tool and the material.

Higher machining parameters (V3) result in faster removal of particles breaking away from the material surface and hence a reduction in cutting forces. at V3 speeds, cutting force values decrease as the diamond grain size increases. It is seen that vibration values also decrease with the decrease in cutting force values. Vacuum diamond tools exhibit a more regular cutting behavior as the tool-material interaction becomes more homogeneous and regular at V3 machining parameters. Here, it is seen that cutting speeds also affect the cutting mechanization. T602 tools have a larger cutting area and higher cutting power. Its strong interaction with the material facilitates the cutting process.

6. Conclusions

Muğla White marble and Bursa White marble have different calcite mineral grain size distributions and textural combinations. These differences; speed changes in cutting parameters and cutting diamond grain structures with different sizes cause various variations in the chip formation process in the contact zone between the workpiece and the insert. The cutting process is carried out by grinding in the cutting zone.

The best results were obtained with T602 diamond tool and 12000 rpm and 3000 mm/min feed rate. Considering these results; Muğla White marble consumed approximately 77% more specific energy and 52% more cutting force (Fc) was applied compared to Bursa White marble. Here, it was concluded that Bursa White marble can be processed more easily. It was determined that the structural properties of the marbles were effective on the cutting performance.

The compatibility between different diamond grain size tools, marble mineral grain size, textural properties and cutting parameter levels (cutting speed and feed rate) was found to be very important for cutting efficiency.

In general, T_{602} diamond size tools are superior to other diamond tools in terms of specific energy and cutting force criteria. However, it can be said that more favorable results are obtained at 12000 rpm and 3000 mm/min feed rate conditions, these speeds are also considered to provide efficiency in terms of operational time in the milling process. Low machining parameters made the tool-material interaction more complex, which reduced the stability of the cut and caused performance variability. At high machining parameters, the force and energy values are more stable as the tool-material interaction becomes more homogeneous and controllable.

Future studies should be carried out on optimization of machining parameters, wear mechanism and tool life of vacuum diamond tools.

Declaration of Ethical Standards

The authors declare that they have adhered to all ethical standards. This study was derived from the doctoral thesis titled "Effect of Diamond Grain Sizes on Cutting Forces and Specific Energy in Marble Milling Processes" with thesis number 10147418 by Oğuzhan ÖZ under the supervision of Assoc. Prof. Dr. Erkan ÖZKAN.

Authorship Contribution Statement

Author 1: Research, Resources, Experimentation, Writing – original draft visualization, Writing – original draft, Analysis and interpretation

Author 2: Research, Resources, supervision, and writing – review & editing, consultancy.

Declaration of Competing Interest

The authors have no conflicts of interest to declare with respect to the content of this article.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

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