



The effect of mineralogy on the microwave assisted cutting of igneous rocks

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Abstract

Hard rocks can be excavated difficultly by some mechanical miners such as roadheaders. Tunnel boring machines (TBMs) can excavate hard rocks, but the cost is high due to low advance rate and high tool wear. The difficulties in hard rock excavation can be overcome by exposing hard rocks to microwave energy while cutting. This study investigates influence of mineralogy on the microwave assisted cutting of igneous rocks. The normal and cutting forces were measured during the cutting tests, and the specific energy values were calculated. The optimum specific energy (SE_{opt}) values reduce quite steadily with the increasing microwave power. The SE_{opt} of some tested crystalline rocks first increases at the low power (3 kW) and then decreases at the high power (6 kW). The losses in the SE_{opt} range from 22.5 to 38.7% at the power of 6 kW. The equations were also developed for the estimation of the SE_{opt} loss. Concluding remark is that the same rock types may be affected differently by microwave energy because of the different mineral types and percentages, and thus they behave diversely under cutting tests. The derived equations will be useful for the prediction of the SE_{opt} loss due to the microwave treatment.

Keywords Microwave treatment · Cutting · Specific energy · Mineralogy · Igneous rocks

Introduction

Rock masses are excavated by drilling and blasting or mechanical excavators in rock engineering projects. Since the mechanical excavation has several advantages compared to drilling and blasting method, it has been widely used for the excavation of rocks in suitable conditions. Although the mechanized excavation has various advantages in tunneling

and mining, it has some drawbacks. When excavating very hard and abrasive rocks, the most important problems are low advance rate and high cutter wear. The worn cutters significantly increase cutting forces and thrust requirement to penetrate cutter into rock, and therefore the performance of machine decreases (Zhang et al. 2020; Chang et al. 2017). On the other hand, if the abrasive rock has high strength, higher cutter loads may result in the failure of bearings of disc cutters; thus, this can trigger the wiping out of the whole cutters of tunnel boring machine (Rostami 2016). In order to solve these problems, several researchers have been studying on some innovative methods such as water-jet assisted cutting, laser-jet assisted cutting, oscillating disc cutting, and microwave assisted cutting.

Recently, the studies on the microwave assisted cutting of hard rocks have been drawing attention. Minerals and rocks are the dielectric materials absorbing microwave energy. The mineral types and percentages determine the dielectric constant of a rock type, thus the heating degree. The heating degree of a rock type irradiated by microwave energy is also affected by grain size, moisture content, ambient temperature, treatment duration, applied microwave power, and the frequency of the microwave energy (Santamarina 1989;

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Peinsitt et al. 2008). Because the dielectric constant of each mineral differs from each other under microwave energy, their heating degrees and the thermal expansions will be different. The differential thermal expansion of minerals creates the internal stresses in the rock texture; thus, cracks occur in the rock structure.

Several scientists have investigated the effects of microwave illumination on the strength and the crack development of rocks to provide a basis for the potential use in the rock excavation (Satish 2005; Satish et al. 2006; Motlagh 2009, 2015; Peinsitt et al. 2010; Nejati et al. 2012; Hassani et al. 2016; Lu et al. 2017, 2019, 2020; Zheng et al. 2017, 2019; Bisai et al. 2020; Kahraman et al. 2020). They revealed that microwave treatment creates cracks on the rock samples and decreases the rock strength depending on the mineral content, the applied microwave power, and the exposure time.

Lindroth et al. (1991) took out a patent for the microwave assisted rock cutting and presented the basic possible design of the microwave treatment of rock block while cutting. In the patent document, only microwave treatment of rock during cutting was theoretically explained. The application of the method has not been performed in the laboratory or in the field. Although a patent was taken in 1991, no research has been carried out on this subject for a long time. Hassani and Nekoovaght (2011) reviewed the studies about the influence of microwave energy on the mechanical properties of some common hard rocks and suggested a schematic possible design of microwave assisted-TBM cutterhead. Hassani et al. (2016) executed the field simulation of microwave exposure of rocks by creating artificial blocks of basalts by stacking 12 slabs with 2 cm thickness and exposed to microwaves at 3 kW power for 60 s or 120 s. The results showed that the measured penetration depth for dry and wet basalts was approximately 5 cm. The highest macrocrack density in the topmost slab was observed when dry basalt sample was irradiated for 120 s at a distance of 3 cm from the antenna. They explained that the microwave assisted rock cutting system was feasible and achievable. Hartlieb and Grafe (2017) irradiated a large granite block with 24 kW open-ended waveguide for the time of 30 s and then cut by a linear cutting machine using a conical cutter. They revealed that the reduction of cutting forces was approximately 10%. In another study, Hartlieb et al. (2017) showed that the cutting force and the specific energy values of granite were reduced by 22% and 6.3–29.8%, respectively, at the exposure time of 45 s with 24 kW power. Shepel et al. (2018) evaluated the cutting forces in cutting large granite sample radiated by high-power microwave energy using multiple regression analysis. They derived multiple regression models including the exposure duration, the spacing between cuts, and the depth of cut for the estimation of the cutting forces. Recently, Feng et al. (2019) took out a patent for the hard rock TBM cutterhead equipped with microwave generating mechanism.

As stated above, only granite samples were previously cut by the conical cutter in the microwave assisted cutting tests (Hartlieb and Grafe 2017; Hartlieb et al. 2017; Shepel et al. 2018). The study investigates the influence of mineralogy on the microwave assisted cutting of nine different igneous rocks such as granite, syenite, basalt, andesite, and diabase. The cutting tests with a mini-disc cutter were performed on block samples which were untreated and treated by microwave, respectively, and the cutting forces were measured. Because specific energy is a valuable parameter in rock cutting (Rostami et al. 1994; Kim et al. 2020), the specific energy values for each rock sample were calculated, and the results were evaluated.

Sampling and mineralogy

The large block samples of nine different igneous rocks were collected from the different locations of Turkey for the laboratory studies. The samples are composed of two granites, one granodiorite, one syenite, one basalt, three andesites, and one diabase (Table 1).

The mineralogical analysis was carried out on the prepared thin sections of each rock type. The mineral constitutions were detected under the polarizing microscope. The percentages of each mineral were determined using the point-counting device. Table 2 presents the types and percentages of each mineral for the rock samples. The mineral percentages in matrix were also determined for the rocks with matrix (Table 3).

Experimental studies

Physico-mechanical tests

The uniaxial compressive strength (UCS), the Brazilian tensile strength (BTS), the density, and the porosity tests were carried out on the NX-size (54.7 mm) air dried core

Table 1 The rock samples included to the study

Rock code	Rock type	Location
1	Granite (Anadolu gri)	Ortaköy/Aksaray
2	Granite (Yaylak)	Sarıyahşi/Aksaray
3	Granodiyorit (Kaman roza)	Kaman/Kırşehir
4	Syenite (Kırçiçeği)	Kaman/Kırşehir
5	Basalt	Bor/Niğde
6	Andesite	Yeşilburç/Niğde
7	Andesite	Azatlı/Niğde
8	Andesite	Erkilet/Kayseri
9	Diabase	Erkilet/Kayseri

Table 2 The mineral constitutes and percentages of the samples

Mineral type	Rock codes and mineral percentages (%)								
	1	2	3	4	5	6	7	8	9
Quartz	8	27	32	-	-	-	-	-	-
Orthoclase	14	44	44	42	-	-	-	-	-
Plagioclase	56	25	14	8	68	47	58	11	53
Biotite	6	2	8	-	4	-	-	1	-
Amphibole	9	2	-	12	6	-	-	1	-
Pyroxene	7	-	-	18	13	17	10	1	28
Olivine	-	-	-	-	-	-	-	-	18
Nepheline	-	-	-	13	-	-	-	-	-
Sphene	-	-	-	5	-	-	-	-	-
Chalcedony	-	-	2	-	-	-	-	-	-
Melanite	-	-	-	2	-	-	-	-	-
Fe-Ti oxide	-	-	-	-	1	1	1	-	1
Matrix	-	-	-	-	8	35	31	86	-

specimens according to ISRM (2007) suggested methods. The average results of the tests are given in Table 4.

Microwave treatment tests

The three prismatic samples with sizes of approximately 25 cm × 18 cm × 10 cm were prepared from each rock type for the linear cutting tests. A 6 kW microwave oven with the frequency of 2.45 GHz was used for the illumination of the samples (Fig. 1). The multi-mode oven has 6 magnetrons with the power of 1 kW. The block samples were placed into the oven and treated entirely with microwaves. The two samples for each rock type were treated by microwave energy at 3 and 6 kW powers, respectively, for the exposure time of 10 min. Since the multi-mode cavity is used and the maximum power is 6 kW, the exposure time of the samples has been kept long in order to reach a significant temperature. An infrared gun was used for the measurement of the surface temperatures of each sample prior to the microwave radiation. After taking the specimens out of oven, their surface temperatures were also measured (Fig. 2). All surfaces of the samples were

scanned by the infrared gun, and the average values were used as the surface temperatures. It was seen that the temperature values of the specimens were scattered. This is due to the inhomogeneous heating of the microwaves depending on the random scattering of microwave in oven and the different microwave absorption capacity of each mineral in a rock type.

Linear cutting tests

The results of this study will be evaluated on the basis of specific energy (SE), since it is an important parameter in rock cutting. SE can be described as the energy required for cutting a unit volume of rock and can be calculated using the following equation (Pomeroy 1963):

$$SE = \frac{FR}{Q} \tag{1}$$

where SE is specific energy (MJ/m³), FR is the average cutting force or rolling force acting on the cutter (kN), and Q is the yield, defined as the volume of rock obtained per unit length of cut (m³/km).

Table 3 The mineral constitutes percentages in matrix for the rocks with matrix

Mineral type	Rock codes and mineral contents in matrix (%)								
	1	2	3	4	5	6	7	8	9
Plagioclase	-	-	-	-	7.4	9.1	4.4	1.5	-
Pyrite + Ilmenite	-	-	-	-	0.6	-	-	-	-
Volcanic glass	-	-	-	-	-	25.3	26.3	63.0	-
Pyroxene	-	-	-	-	-	0.3	0.3	-	-
Sanidine	-	-	-	-	-	-	-	9.8	-
Opaque mineral	-	-	-	-	-	0.3	-	0.7	-

Table 4 The physico-mechanical test results of the untreated specimens

Rock code	UCS (MPa)	BTS (MPa)	Density (g/cm ³)	Porosity (%)
1	144.6±11.2*	11.9±1.4	2.58±0.07	1.17±0.12
2	106.9±6.6	9.4±1.0	2.63±0.01	1.21±0.04
3	114.2±13.1	7.4±0.4	2.60±0.02	1.44±0.01
4	107.1±5.4	6.8±0.9	2.57±0.03	1.57±0.19
5	119.0±13.1	13.5±1.0	2.64±0.01	4.51±0.27
6	114.6±6.6	6.7±0.8	2.48±0.05	7.20±0.44
7	124.6±6.1	8.0±1.2	2.43±0.00	6.20±0.28
8	74.7±8.4	7.0±0.4	2.25±0.04	13.47±0.16
9	77.1±5.4	7.5±0.6	2.50±0.04	5.83±0.63

*Standard deviations

The relieved rock cutting tests were performed using a portable linear rock cutting machine (PLCM). The PLCM was first developed by Balci et al. (2016). As shown in Fig. 3, the PLCM used in this study is the same as that developed by Balci et al. (2016). It generally consists of a rigid body on which the cutter and loadcell are mounted and a table where the sample box is placed and that moves with servo-controlled hydraulics cylinder. The machine was equipped with a 144-mm diameter CCS-type mini disc cutter with the tip width of 2 mm. The detailed technical specifications of PLCM are available in the paper published by Comakli et al. (2021).

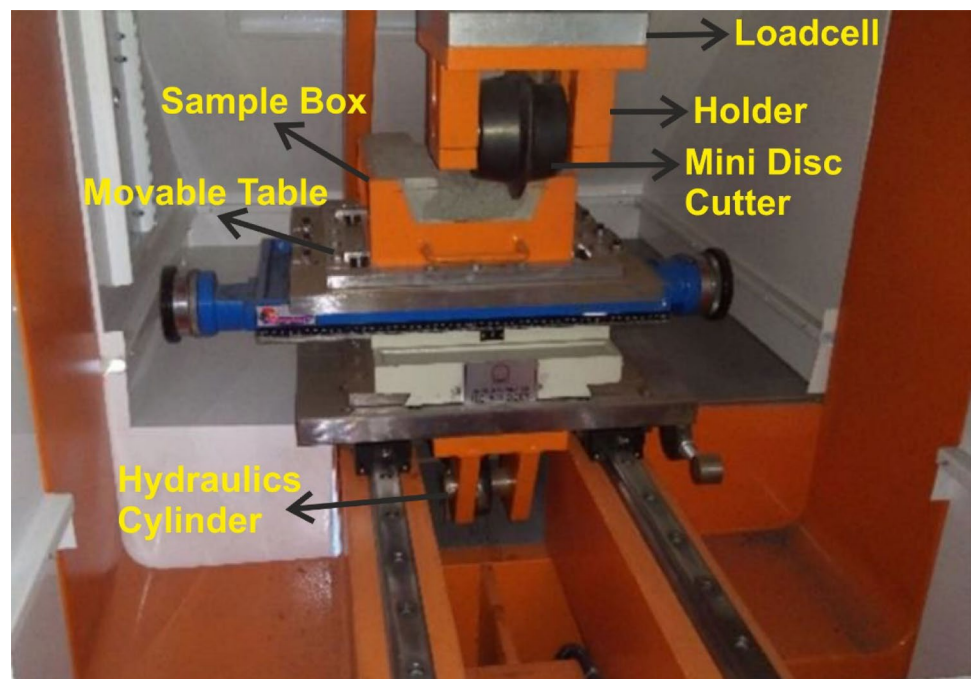
**Fig. 1** The 6 kW microwave oven used in the tests**Fig. 2** The measurement of the surface temperatures

Large prismatic samples, one untreated and two treated for each rock type, were cemented into the steel test boxes using the cement-based grouts and left to set for 1 day before testing (Fig. 4). The surfaces of the samples were trimmed with the cutters prior to the cutting tests. The cutter spacings (s) were kept as 15 mm, and the depth of cuts (d) were selected as 1, 2, and 4 mm.

Before starting the rock cutting tests, fresh rock surface was obtained by two or three trimming passes using the mini-disc cutter to simulate the real case of rock surface excavated by TBM in the field. The surface of the rock was then conditioned with at least two or three passes, depending on rock characteristics. Figure 5 shows the conditioned sample surface and the design of cutting test parameters.

The relieved cutting tests (there are interaction between the cutting lines) were executed at a cutting speed of 3 cm/s, and the normal and rolling (cutting) forces were measured by the dynamometer fixed on the cutter. The forces in the first and last two cuts in the data pass were not recorded, since irregular fracture conditions occurred at these excavation lines. In addition, data from the beginning and end of each cut were not included in the data analyses to discard the edge effects on the data. After each cut, muck was collected and weighed to determine the mass. Then, the mass of muck was divided by rock density, and the yield was calculated. The data from 3 to 5 cuts were analyzed for each depth of cut, and the average SE values were calculated using Eq. (1). Figure 6 indicates the surface condition of the two samples after the cutting test.

Fig. 3 Portable linear rock cutting machine (PLCM)



It is normally necessary to add the SE expended by the applied microwave to the SE expended for cutting. However, whole block is heated in multi-mode cavities, but only a very small part of it is cut. The calculation of the energy to heat only the surface to be cut is impossible due the fact that microwaves are randomly distributed in multi-mode cavities and only some of waves come into contact with the sample. In other words, only a very small amount of the microwave energy which cannot be calculated or estimated is used for heating in multi-mode cavities. Therefore, the energy of micro-wave heating cannot be considered. It is aimed in this study to show the SE difference of cutting between the samples untreated and treated by microwave without considering the energy of micro-wave heating.

Results and discussions

Evaluating the surface temperatures of the treated samples

Figure 7 illustrates the surface temperatures of the specimens as a function of microwave power. Although the temperatures of most specimens do not increase much (less than 100 °C) at 3 kW power, the temperatures of andesite (Erkilet) and diabase (Erkilet) reach significant level (about 170 °C). At 6 kW power, it is seen that the temperature values are quite scattered, and the temperature of some samples are quite high. Even though the granites and granodiorites mostly consist of quartz, feldspar, and plagioclase

Fig. 4 Block samples placed in the steel sample box by the cementing process



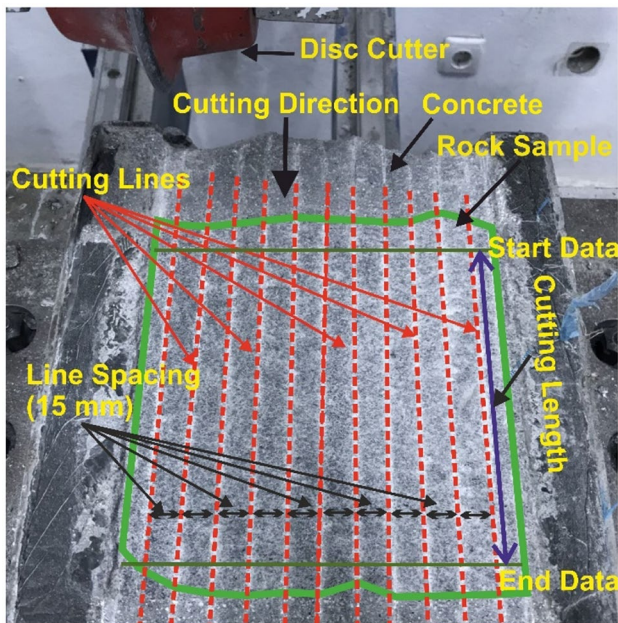
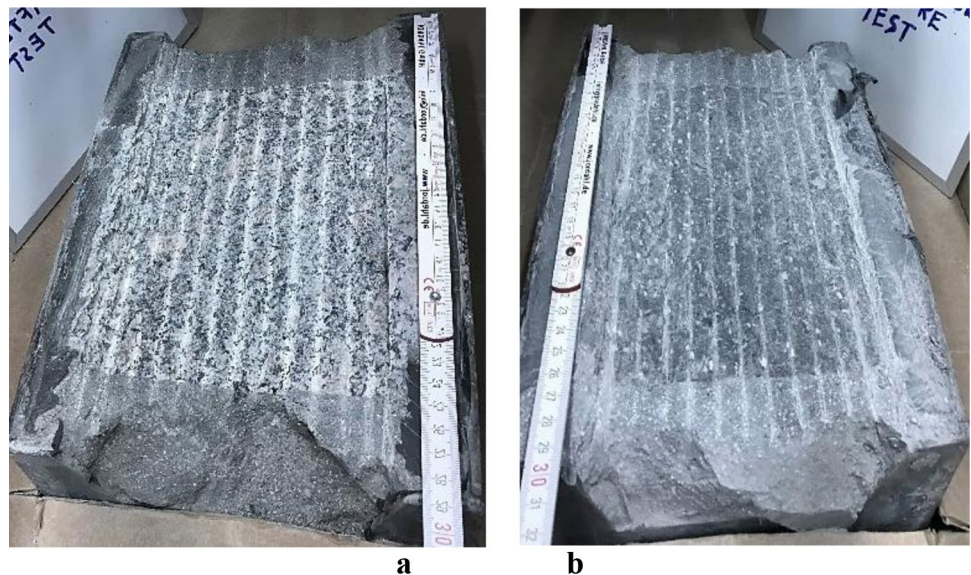


Fig. 5 Conditioned rock surface and the design of cutting test parameters

which absorb microwave energy less compared to some other minerals (Chen et al. 1984; Walkiewicz et al. 1988), the temperatures of tested granites raised to significant level at 6 kW. That the temperatures of the granites (about 220 °C) are higher than that of the granodiorite (170 °C) is due to the fact that the granites have microwave absorber minerals such as amphibole and pyroxene. Although the basalt has low temperature (82 °C) at 3 kW power, it has high temperature (290 °C) at 6 kW power. The syenite specimen has a quite high temperature (246 °C) at 6 kW

Fig. 6 The surface condition of granodiorite (Kaman rosa) (a) and andesite (Yeşilburç) (b) after the cutting test



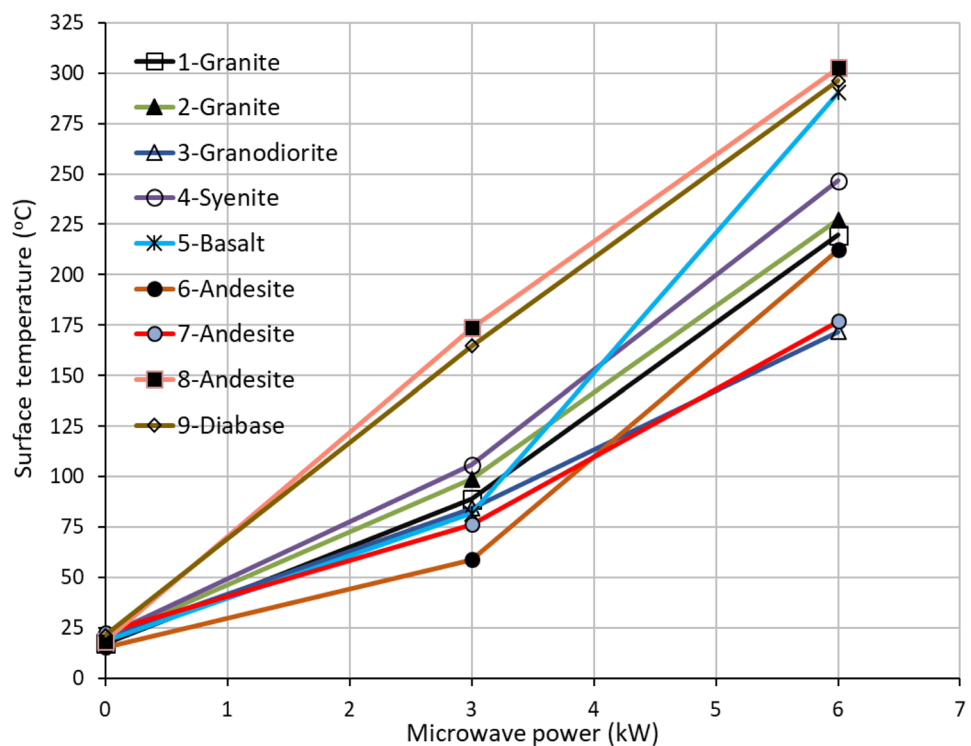
power. The temperatures of andesite (Yeşilburç), andesite (Azatlı), and andesite (Erkilet) are 212 °C, 177 °C, and 302 °C, respectively, at 6 kW power. That the temperatures of the three different andesite types are different from each other is because they have different mineralogy. Since andesite (Azatlı) has the highest plagioclase content, it has the lowest temperature. On the other hand, because andesite (Erkilet) has the lowest plagioclase content and the highest volcanic glass, it has the highest temperature. The temperature of diabase is also high (296 °C) at 6 kW power due to the significant amount of microwave absorber minerals such as pyroxene and olivine.

Evaluating the results of linear cutting tests

The plots of the cutting forces as a function microwave power are given in Fig. 8 for the different depth of cuts. The SE values and the debris volumes as a function of microwave power are also shown in Fig. 9. As cutting force increases, if debris volume increases more than cutting force increment, SE will decrease. Therefore, the assessment of cutting forces alone can be misleading. For this reason, the cutting forces, the debris volumes, and the SE values are evaluated together at the following paragraph:

For granite (Anadolu gri) sample, the cutting and normal forces at 3 kW power are higher than that of at 0 and 6 kW powers. The cutting forces at 0 and 6 kW powers are almost the same for all depth of cut conditions, while normal forces at 6 kW power are lower than that of at 0 kW power. (Fig. 8a). As shown in Fig. 9a, The SE values at 6 kW power for all depth of cut conditions are lower than that of at 0 kW. However, the SE values at 3 kW power for 2 and 4 mm depth of cuts are higher than that of at 0 and 6 kW powers in accordance with Fig. 8a. But the SE value at 3 kW

Fig. 7 The surface temperatures of the specimens as a function of microwave power



power for 1 mm is unexpectedly very low compared to the SE values at 0 and 6 kW powers due to the high volume of debris. This may be due to the heterogeneous heating of the microwaves and/or the heterogeneity of the coarse-grained minerals. The heterogeneity of the minerals is illustrated in (Fig. 10). Plagioclase, orthoclase, and biotite minerals are accumulated in the areas labelled 1. Quartz minerals are concentrated in the areas labelled 2. Because the hardness of plagioclase, orthoclase, and biotite minerals is lower than that of quartz, the cutting forces show abnormal values when cutting the areas 1 and 2.

For granite (Yaylak) sample, the cutting forces do not change much with the increasing power for 1 and 2 mm depth of cuts. However, for 4 mm depth of cut, the cutting force and normal force increase too much at 3 kW power and then decrease at 6 kW power (Fig. 8b). As depicted in Fig. 9b, The SE value at 3 kW power is higher than that of at 0 and 6 kW powers in line with Fig. 8b for 4 mm depth of cut. While the SE values decrease for 1 and 2 mm depth of cuts, the debris volume increases with the increasing power. The normal forces show different trends for 1 and 2 mm depth of cuts. It is thought that the abnormal values of the forces and the SE value for 4 mm depth of cut are because microwaves heat materials heterogeneously and granite (Yaylak) has a heterogeneous texture due to the coarse grains. When cutting coarse-grained rocks, because some coarse grains of hard minerals such as orthoclase (Fig. 11) cannot be broken by cutter, cutting force and SE increase much.

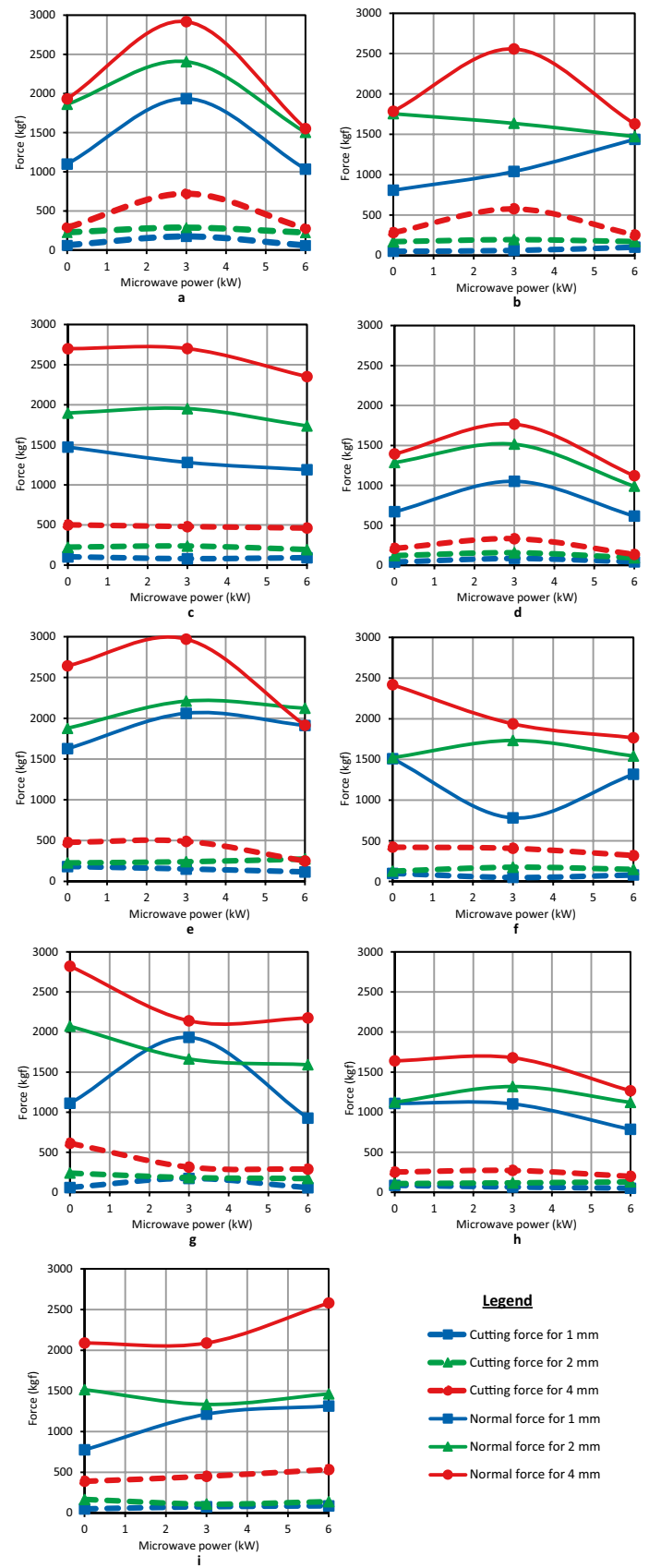
For granodiorite (Kaman roza) sample, the cutting forces do not change much with the increasing power for all depth of cut conditions (Fig. 8c). But since the debris volumes increase with the increasing power, the SE values decrease with the increasing power (Fig. 9c). The normal forces at 2 and 4 mm depth of cuts indicate slight increments. The reasons for these increments is probably due to the coarse orthoclase grains (Fig. 12).

For syenite sample, the cutting and normal forces at 3 kW power are higher than that of at 0 and 6 kW powers (Fig. 8d). Normal forces at 6 kW power are lower than that of at 0 kW power. The SE values at 3 kW power are almost the same as the SE values at 0 kW power due to the high volume of debris. The SE values at 6 kW are lower than that of at 0 and 3 kW powers. The curves almost overlap for 1 and 2 mm depth of cuts (Fig. 9d). The abnormal values are probably due to the heterogeneity of the minerals as illustrated in Fig. 13. The accumulated quartz minerals which are harder than the other minerals in different areas of syenite cause heterogeneous heating and force differences.

For basalt sample, while the cutting and normal forces show different trends with the increasing power for the different depth of cut conditions (Fig. 8e), the SE values exhibit the same trend for all depth of cut conditions. The SE values decrease with the increasing power (Fig. 9e).

For andesite (Yeşilburç) sample, the cutting and normal forces show different tendencies with the increasing power for the different depth of cut conditions (Fig. 8f). The SE values decrease with the increasing power for all depth of cut

Fig. 8 The cutting (rolling) and normal forces as a function of microwave power: **a** granite (Anadolu gri), **b** granite (Yaylak), **c** granodiorite (Kaman roza), **d** syenite, **e** basalt, **f** andesite (Yeşilburç), **g** andesite (Azatlı), **h** andesite (Erkilet), **i** diabase



conditions. The lines almost overlap for 2 and 4 mm depth of cuts (Fig. 9f).

For andesite (Azatlı) sample, the cutting and normal forces as a function of power show different trends for the different depth of cut conditions (Fig. 8g). The SE values at 2 and 4 mm depth of cuts decrease with the increasing power. For 1 mm depth of cut, although the cutting force is high at 3 kW power, the SE is low since the debris volume increases about three times compared to debris volume at 0 kW (Fig. 9g).

For andesite (Erkilet) and diabase samples, the cutting and normal forces show different trends with the increasing power for the different depth of cut conditions (Figs. 8h, i). But the SE values of the two samples decrease with the increasing power for all depth of cut conditions (Figs. 9h, i).

The relations between the specific energy (SE) values and the spacing-to-depth (s/d) ratios are shown in Fig. 14 for the untreated and the treated specimens of each rock type, respectively. The optimum specific energy ($SE_{opt.}$) values as a function of microwave power are also indicated in Fig. 15.

There are some anomalies in some plots such as the curves in Fig. 14a for the 3 kW power, in Fig. 14c for the 6 kW power, and in Fig. 14g for the 3 kW power. It is expected that the SE values at high s/d ratio should be higher than the $SE_{opt.}$. However, the SE values at high s/d ratio are less than the $SE_{opt.}$ for the mentioned plots. This is probably due to the inhomogeneous heating of the microwaves and/or the heterogeneity of rocks as stated above.

One of the important results which can be drawn from Figs. 14 and 15 is that the $SE_{opt.}$ values at 3 kW power are higher than that of the untreated conditions (0 kW) for granite (Anadolu gri), granite (Yaylak), and syenite (Figs. 14a, b, d, and 15a, b, d). For the mentioned rocks, the $SE_{opt.}$ values decrease at 6 kW power compared to that of the values at 0 and 3 kW powers. These results are compatible with the previous investigations. While some investigators revealed that there was a steady decrease in the strength of granite heated at low temperature by microwave energy (Zeng et al. 2019; Hu et al. 2019; Bisai et al. 2020) or electrical resistance (Yin et al. 2016; Xu and Zhang 2018; Hu et al. 2019), the others found out the increase in the strength of granite heated at low temperature by microwave energy (Hassani et al. 2016) or electrical resistance (Shao et al. 2015; Chen et al. 2017; Qin et al. 2020). The differences between the findings of the researchers are most likely because the strength of the heated rock is also affected by grain size, micro-structural properties, and porosity in addition to the mineral type and percentages. That the increment in the strength of the crystalline rocks at low temperature is explained by the two mechanism as given in the following paragraph.

Sygała et al. (2013) express that if the crystalline rocks are heated at low temperature, the contact surfaces among

grains increase due to the thermal expansion; thus, this results in the increase in the strength of rock. The micro/macro-cracks occur with the increasing temperature, and then the decrement in the strength is observed. Saiang and Miskovsky (2012) showed that ferrous minerals such as biotite (mica), olivine, and pyroxene undergone phase change and formed iron-oxides and alloys at low temperature. The iron-oxides and alloys increased the rock strength even though the micro-cracks were developed. At the increased temperature, the micro-crack developments increased, and the strength of rock was reduced. These findings explain the $SE_{opt.}$ increment at the treatment of low power for some rocks. The increase on the strength also increases the $SE_{opt.}$

The $SE_{opt.}$ values of the tested rock types except the above-mentioned three rocks decrease quite steadily with the increasing microwave power. In order to make a comparison among the tested rocks in terms of the $SE_{opt.}$ values, the percentage changes in the $SE_{opt.}$ values were calculated for each rock type and each power level (Table 5). The increments in the $SE_{opt.}$ values at 3 kW power for granite (Anadolu gri), granite (Yaylak), and syenite are 51.7%, 2.8%, and 4.3%, respectively. The percentage decrease in the $SE_{opt.}$ values of these rocks at 6 kW power ranges from 24.8 to 33.2%. Among the crystalline rocks, granite (Kaman roza) has the lowest decrement in the $SE_{opt.}$ value. This is because granite (Kaman roza) has not microwave absorber minerals such as amphibole and pyroxene. The $SE_{opt.}$ reduction of basalt sample is 24.1% for 6 kW power, which is low compared to granite (Anadolu gri) although both rock types have quite similar amount of amphibole and pyroxene. This is probably due to the fact that basalt has high content of plagioclase and its porosity (4.51%) is quite higher than that of granite (Anadolu gri) (1.17%). During microwave heating, the micro-crack developments in the high-porosity rocks will be lower than that of the high-porosity rocks for the similar mineralogy because some of the thermal stresses will be absorbed by the pores. The $SE_{opt.}$ decrements of the two andesite types (Yeşilburç and Azatlı) are approximately the same as that of the crystalline rocks. However, andesite (Erkilet) has the highest decrement (38.7%) in the $SE_{opt.}$ at 6 kW power among the tested rock types. It has a decrement of 30.0% in the $SE_{opt.}$ even at 3 kW power. The reason behind the high $SE_{opt.}$ decrement of andesite (Erkilet) is the low percentages of microwave non-absorber minerals and the high percentage of microwave absorber mineral (volcanic glass) in the matrix. The $SE_{opt.}$ reduction of diabase is almost the same as that of andesite (Erkilet) for both power levels. That the $SE_{opt.}$ decrease of diabase is high is due to the high percentage of pyroxene and olivine minerals, which is 46% in total.

As stated above, Hartlieb et al. (2017) stated that the SE values of granite exposed to microwaves at 24 kW power for 45 s were decreased by 6.3–29.8%. In this study, the exposure time was selected as 10 min to see some decrement on the

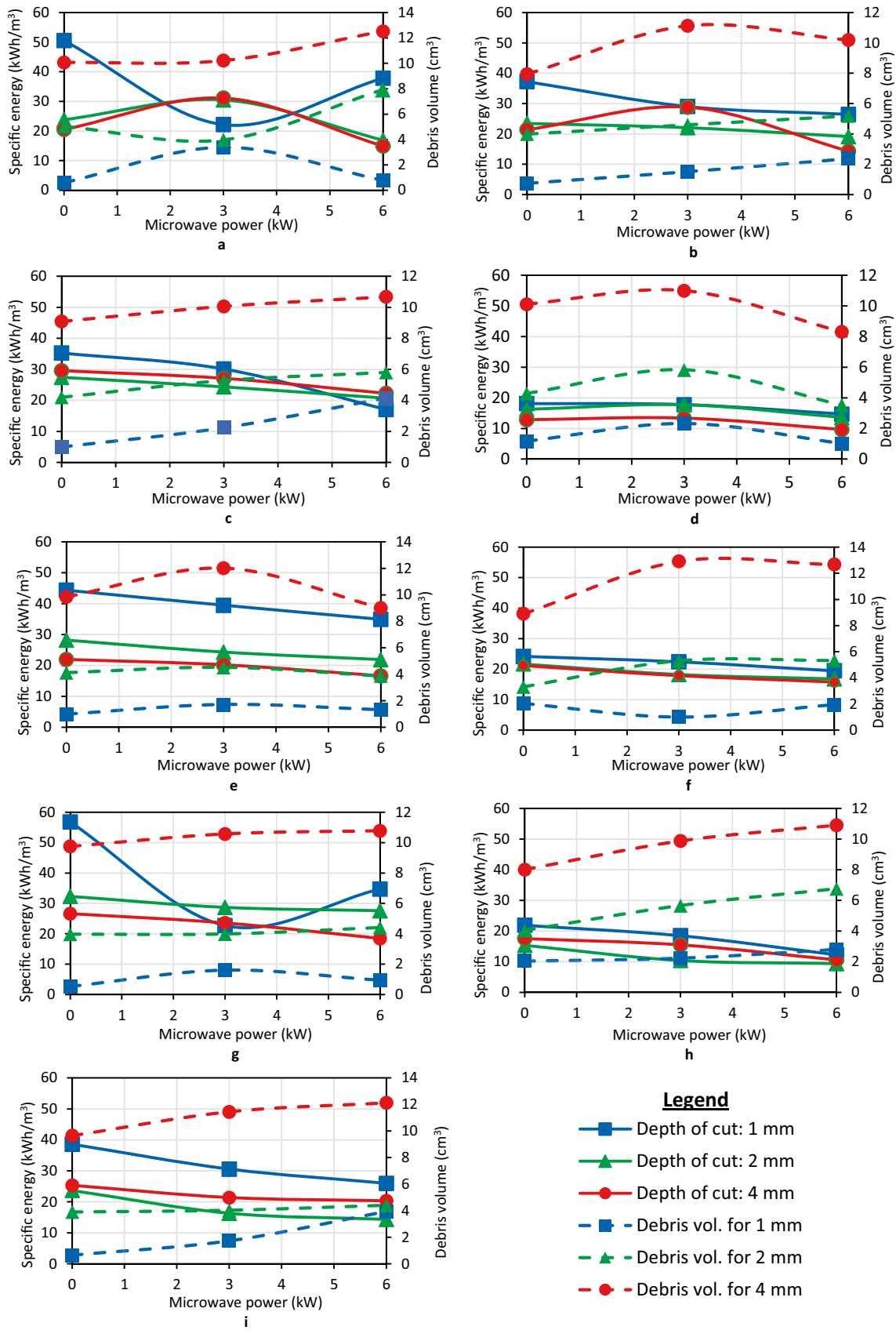


Fig. 9 The specific energy and debris volume as a function of microwave powers: **a** granite (Anadolu gri), **b** granite (Yaylak), **c** granodiorite (Kaman roza), **d** syenite, **e** basalt, **f** andesite (Yeşilburç), **g** andesite (Azatlı), **h** andesite (Erkilet), **i** diabase

specific energy of cutting because a multi-mode microwave oven has the maximum power capacity of 6 kW. It is evident from the literature (Motlagh 2009; Kahraman et al. 2020) that the surface temperature of rock increases and the strength decreases as the power increases. It can be said that the SE reductions obtained would occur in less than 60 s if the microwave power more than 20 kW could be applied in this study.

Fig. 10 The heterogeneity of the minerals for granite (Anadolu gri) sample: The accumulation of plagioclase, orthoclase, and biotite minerals in redlined areas. The accumulation of quartz minerals in yellowlined areas

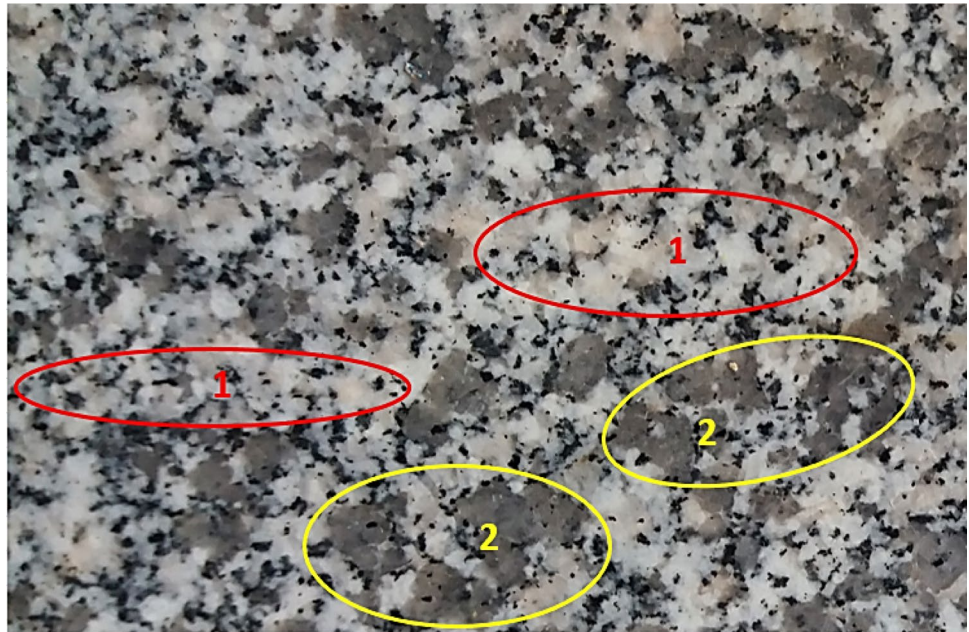


Fig. 11 Coarse orthoclase grains (in redlined areas) in granite (Yaylak) sample



The derivation of the prediction equation for the $SE_{opt. loss}$

It was also investigated the correlations between the $SE_{opt. loss}$ at 6 kW power and both the percentages of microwave absorber (MA) and non-absorber (MnA) minerals. For the tested rocks, the minerals that can be accepted as microwave absorber are amphibole, pyroxene, biotite, olivine, sphene, melanite, and Fe-Ti oxide. There is no information about the volcanic glass in the literature if it is microwave absorber or not. A volcanic glass (Obsidian) sample was heated in the microwave oven at 6 kW power to determine its capacity to

absorb microwave energy. It was seen that the surface temperature of the obsidian reached about 200 °C for 5 min and about 400 °C for 10 min. These temperature values are quite higher than that of the temperatures of the tested samples. Therefore, the volcanic glass was accepted as microwave absorber mineral. There is a moderate correlation between the SE_{opt} loss and the MA as illustrated in Fig. 16. Quartz and feldspar are found abundantly in igneous rocks and known as MnA minerals. Quartz plus feldspar content was used as the MnA mineral content. As indicated in Fig. 17, the correlation between the SE_{opt} loss and the MnA is also moderate. That the correlations between the SE_{opt} loss and

Fig. 12 Coarse orthoclase grains (in redlined areas) in granite (Kaman roza) sample

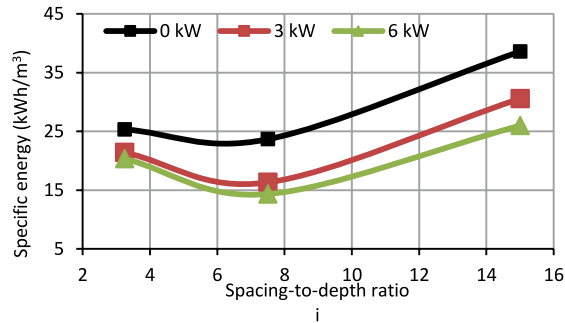
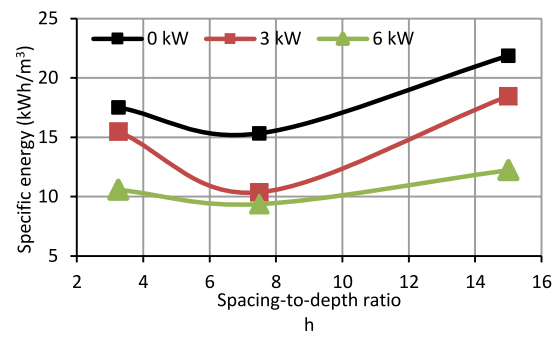
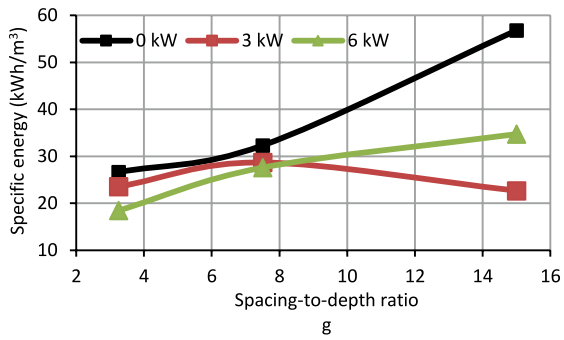
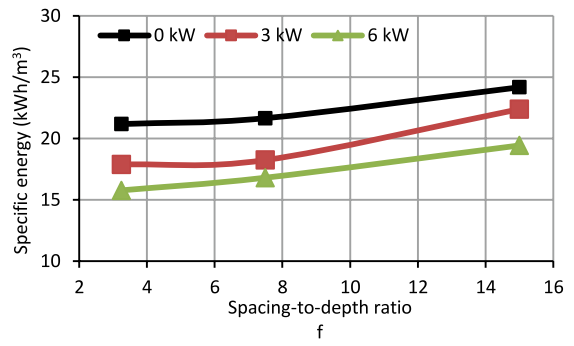
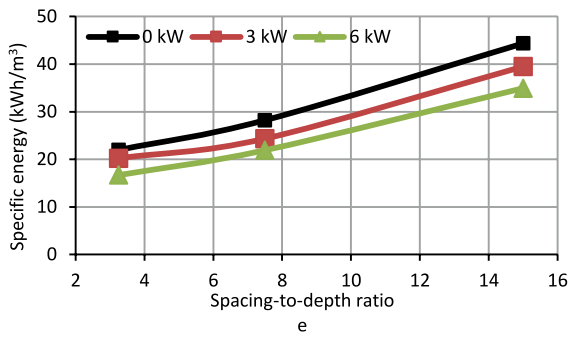
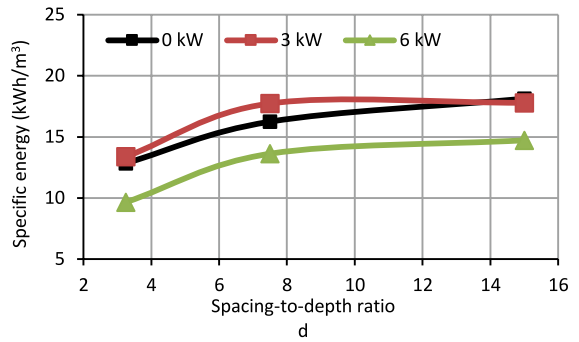
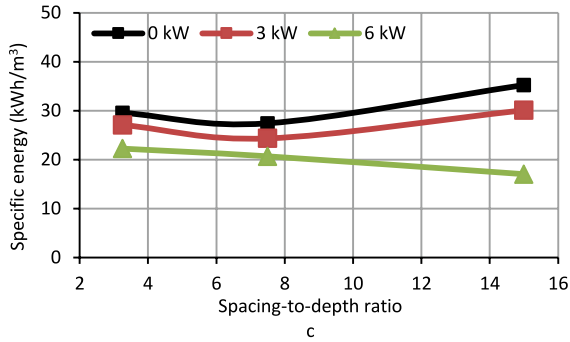
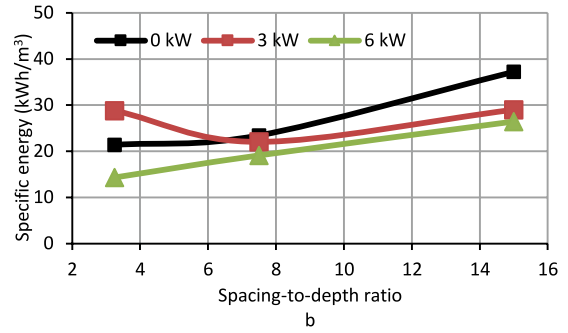
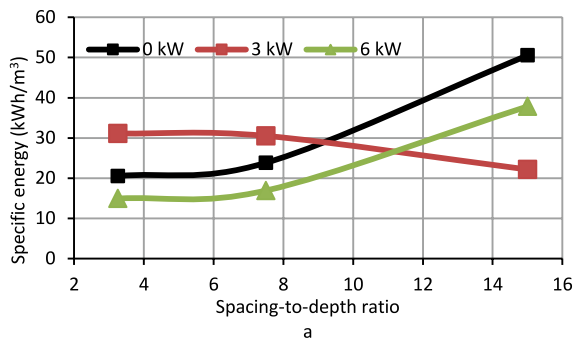


Fig. 13 The accumulation of quartz minerals (in redlined areas) in the syenite sample



Fig. 14 The relations between the specific energy and the spacing-to-depth ratio for different microwave powers: **a** granite (Anadolu gri), **b** granite (Yaylak), **c** granodiorite (Kaman roza), **d** syenite, **e** basalt, **f** andesite (Yeşilburç), **g** andesite (Azatlı), **h** andesite (Erkilet), **i** diabase

both the MA and the MnA are not strong is probably due to the fact that the heating degree, and therefore, the SE_{opt} loss of rocks is also affected from other rock properties. For this reason, multiple regression analysis was carried out including the other rock properties to the analysis and the following equations were developed:



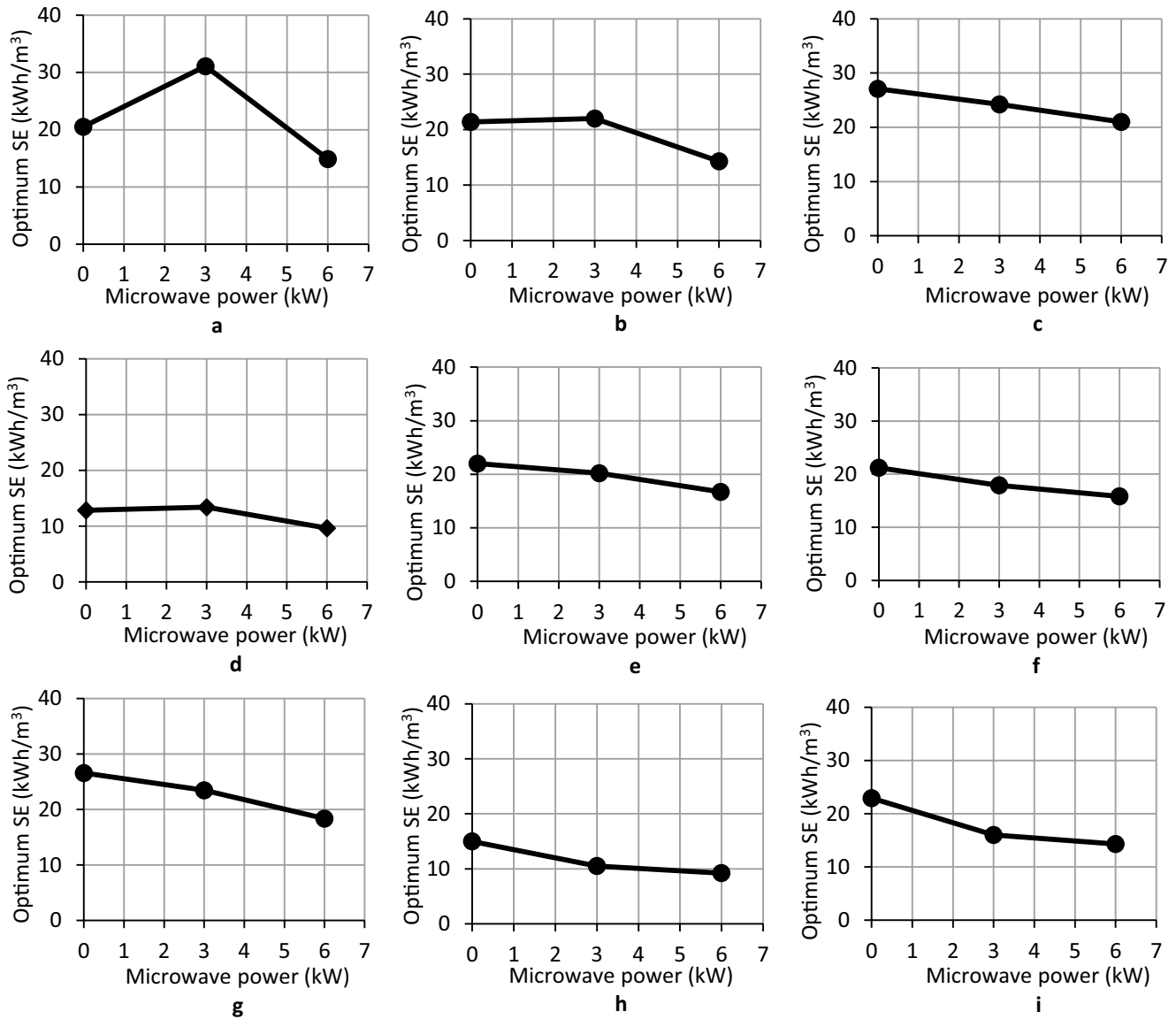


Fig. 15 Optimum specific energy values as a function of microwave power: **a** granite (Anadolu gri), **b** granite (Yaylak), **c** granodiorite (Kaman roza), **d** syenite, **e** basalt, **f** andesite (Yeşilburç), **g** andesite (Azatlı), **h** andesite (Erkilet), **i** diabase

Table 5 The changes in the $SE_{opt.}$ values for the different power levels

Rock code	The changes in the $SE_{opt.}$ values (%)	
	For 3 kW power	For 6 kW power
1	+51.7	-27.3
2	+2.8	-33.2
3	-10.7	-22.5
4	+4.3	-24.8
5	-8.2	-24.1
6	-15.6	-25.5
7	-11.7	-30.8
8	-30.0	-38.7
9	-30.1	-37.6

$$SE_{opt.(loss)} = -0.09MA - 0.16\sigma_c - 38.06\gamma - 0.26n + 147.48r = 0.79 \tag{2}$$

$$SE_{opt.(loss)} = 0.13MnA - 0.18\sigma_c - 49.32\gamma - 0.41n + 167.33r = 0.82 \tag{3}$$

where $SE_{opt.(loss)}$ is the optimum specific energy loss (%), MA is the percentages of microwave absorber minerals (%), MnA is the percentages of microwave non-absorber mineral (quartz plus feldspar) minerals, σ_c is the uniaxial compressive strength (MPa), γ is the density (g/cm^3), and n is the relative porosity (%), and r is the correlation coefficient.

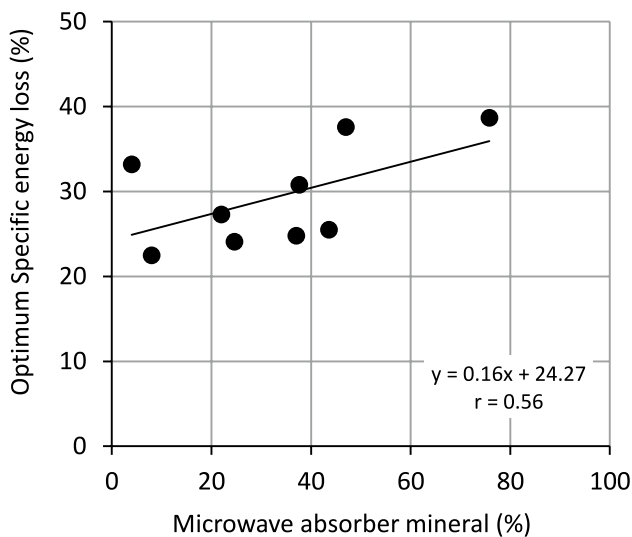


Fig. 16 The correlation between the SE_{opt.} and the MA

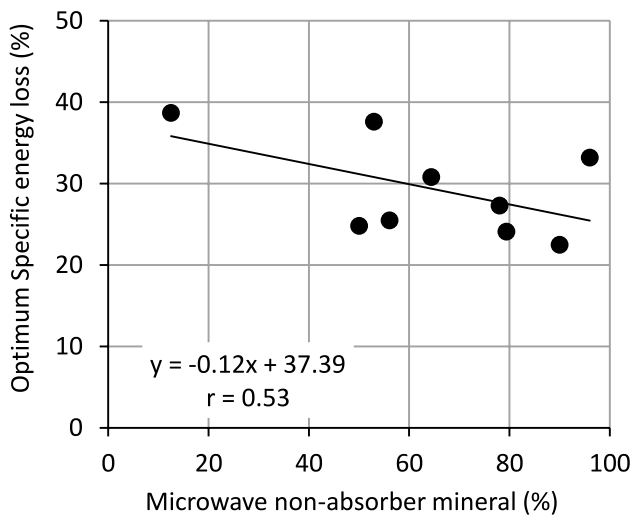


Fig. 17 The correlation between the SE_{opt.} and the MnA

Conclusions

The effects of microwave radiation were studied on the cuttability of nine different igneous rocks having different mineralogical properties. The conclusions that can be drawn from the study are given below:

- The behaviors of crystalline rocks under low microwave energy are different from each other. The SE_{opt.} of some granite and syenite samples first increase at the low microwave power and then decrease at the high power. On the other hand, the SE_{opt.} of a granite sample reduces stably with the increasing microwave power.

- The SE_{opt.} values of crystalline rocks which are known as the microwave non-absorber rocks at low microwave power decline significantly at the microwave power of 6 kW.
- The SE_{opt.} values of basalt, andesite, and diabase decrease steadily with the increasing microwave power.
- The percentage decrement in the SE_{opt.} varies from 22.5 to 38.7% at the microwave power of 6 kW. The highest decrements are observed in the rocks including strong microwave absorbing minerals such as olivine, pyroxene, amphibole, and volcanic glass.
- The derived equations are strong enough for the estimation of the SE_{opt.} loss from the mineral contents and the rock properties.

It is concluded that even if the types of two rocks exposed to microwave are the same, the degree of influence from microwave energy may be different due to different mineral types and percentages, and therefore their behaviors under cutting test differ from each other. The SE_{opt.} loss due to the microwave treatment can be predicted from the derived equations. However, the exposure time applied in this study is long for the actual cutting conditions. In order to see the effects of the shorter exposure times such as 20 or 30 s on the cuttability of rocks, the microwave treatment tests should be further carried out using the high powers such as 20 or 30 kW.

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Declarations

Conflict of interest The authors declare no competing interests.

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