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Investigation on the Usage of Some Non-Almandine Garnet Minerals as Abrasive Material in Waterjet Cutting

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ABSTRACT

In this study, some non-almandine garnet minerals were investigated in terms of their usage possibilities as alternate abrasive materials in waterjet cutting operations. For this purpose, garnet samples were taken from various deposits and mineralization zones in Turkey. These samples were crushed, ground, screened, concentrated and prepared as having desired particle size distribution, and then used in waterjet cutting practices performed on different materials. Cut surfaces were also investigated by measuring the roughness of the surfaces formed after waterjet cutting. At the result of this study, it is observed that quality of the cut surfaces were very close to each other, thus other garnet minerals such as grossularite, andradite, and spessartite can be used for this purpose efficiently.

Keywords: Garnet minerals, Abrasive, Waterjet cutting, Cut surface quality

1. INTRODUCTION

Abrasive waterjet (AWJ) cutting method has been used for cutting and processing of materials for a long time because of its being cold, damage free and precisious cutting technique. First cutting attempts using this method were carried out in California, USA, in 1852 to erode gold-bearing rock. Then it was adapted to the mining of steeply dipping coal seams [1], and after that, hydraulic coal mining has been applied around the world. By increasing the pressure of the water it became powerful enough to use in cutting rocks [2, 3]. By 1970, the waterjet method began to be used in industry to machine materials in nontraditional machining operations [4-6].

Different types of abrasives are used in AWJ machining like garnet, olivine, aluminum oxide (Al_2O_3), silica-sand, glass bead, silicon carbide (SiC), zirconium, etc. But a survey shows that 90% of the AWJ machining is done using garnet [7, 8]. Garnet is the name of a group of iron-aluminum silicate minerals having similar physical properties, crystal forms, and general chemical formula. Garnet has the advantage of containing no free silica and thus it cannot cause silicosis. AWJ cutting requires consistent grading, good cutting speed, and durability, all of which garnet grains provide. Although the electric furnace products such as aluminum oxide (Al_2O_3) and silicon carbide (SiC) has a suitable grain shape and hardness for AWJ cutting they cause excessive amount of wear in nozzles. They can be used only in cutting of very hard materials.

Almandine type garnet mineral is generally preferred in AWJ cutting applications because of its high density and hardness. But as a product of metamorphism occurred in nature other types of garnet mineral are also common. Their usage possibilities will give a chance to evaluation of them. This study invetigates the usage of these garnets in waterjet cutting applications.

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1.1. Main Parts of the AWJ System

An AWJ cutting system consists of five main parts: a high pressure pump (mostly intensifier type), providing high-pressure water; a cutting head, producing the abrasive waterjet; an abrasive delivery system, carrying abrasive grits to the cutting head; a computer control unit, which supplies the desired motion of the cutting head; and a catcher, which absorbs the remaining jet energy after cutting [9, 6]. A typical system is schematically given in Fig. 1.

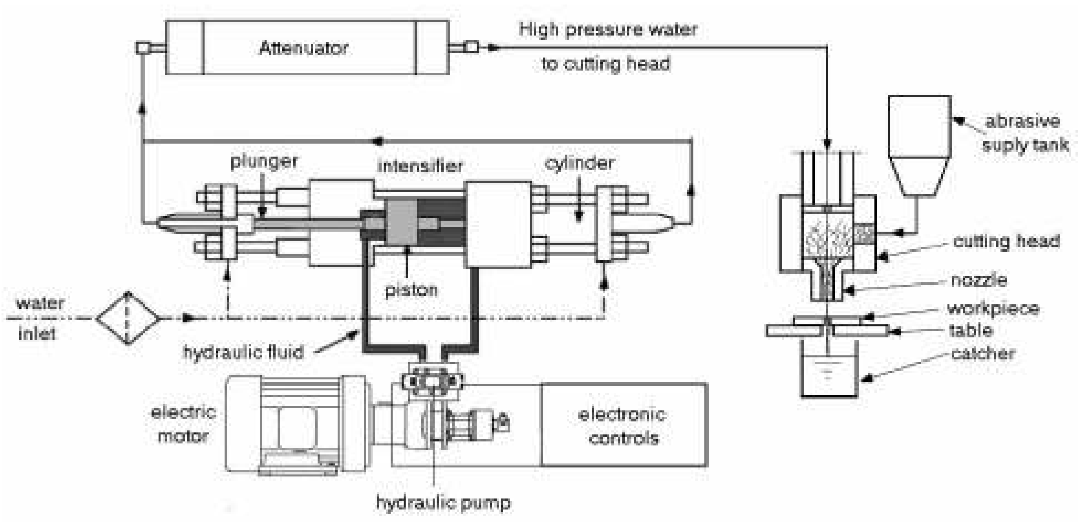

Fig. 1. General layout of an AWJ cutting system [10, 11, 6]

In the intensifier unit (Fig. 1), low-pressure hydraulic fluid is converted into ultra high-pressure water by reciprocating piston-plunger system. The basic technology is both simple and extremely complex. Hydraulic oil pressurized to a pressure of, for example, 20 MPa pushes against a piston biscuit. A plunger with a face area of 20 times less than the biscuit pushes against the water. Therefore, 20 MPa oil pressure is intensified twenty times yielding 400 MPa water pressure. Biscuit/plunger area ratio determines the intensification ratio. Although the principle is simple, to generate and control such a ultra high-pressure water is complex and requires advanced material science and technology.

Cutting head is the other important part of the AWJ cutting system. The cutting head converts the pressurized water into a cutting instrument. High-pressure water being forced through a small hole (typically called the "orifice" or "jewel") creates a high-velocity very thin beam of water traveling as close to the speed of sound. The three common types of orifice materials (sapphire, ruby, diamond) each have their own unique attributes. Sapphire is the most common orifice material used today. It is a man-made, single crystal jewel. Pure waterjet orifice diameter ranges from 0.1 to 1.0 mm for typical cutting. Pure waterjets use the beam of water exiting the orifice to cut soft material like diapers, candy bars, and thin soft wood, but are not effective for cutting harder materials. An abrasive waterjet starts out the same as a pure waterjet. As the thin stream of water leaves the jewel, however, abrasive is added to the stream and mixed. The high-velocity water exiting the jewel creates a vacuum which pulls abrasive from the abrasive line, which then mixes with the water in the mixing tube. The mixing tube acts like a rifle barrel to accelerate the abrasive particles. They, like the orifice, come in many different sizes and replacement life. Mixing tubes are approximately 80 mm long, 6 mm in diameter, and have internal diameters ranging from 0.5 to 1.5 mm, with the most common being 1.0 mm. The beam of water accelerates abrasive particles to speeds fast enough to cut through much harder materials. The abrasive waterjet differs from the pure waterjet in just a few ways. In pure waterjet, the supersonic water stream erodes the material. In the abrasive waterjet, the waterjet stream accelerates abrasive particles and those particles, not the water, erode the material. The abrasive waterjet is hundreds, if not thousands of times more powerful than a pure waterjet. Both the waterjet and the abrasive waterjet have their place. Where the pure waterjet cuts soft materials, the abrasive waterjet cuts hard materials, such as metals, stone, composites and ceramics.

2. MATERIALS AND METHOD

In this research, usage possibilities of some garnet minerals collected from different regions in Turkey for AWJ cutting purposes were investigated. The garnet minerals were taken from Bursa-İnegöl, Bursa-Uludağ, Kırşehir-Kaman and Uşak regions by field studies. These regions are possible garnet deposits determined by the previous researches carried out for different mine exploration purposes [12, 13].

The garnet samples taken from the study areas were first prepared as having desired particle size distribution by crushing, grinding and sieving. Then they were used as abrasive medium in cutting of marble, granite, aluminum, and steel materials as having different density, hardness and strength properties with AWJ cutting machine. In rating of the quality of the cut surfaces and also assessment of the cutting performance of the garnet minerals, all of the cut surfaces were investigated by stylus type roughness tester. Thus, performances of the garnet minerals were compared with each other and with also commercial almandine type garnet abrasive.

2.1. Sampling of the Garnet Minerals in the Study Area

Study area in which the garnet minerals were collected is given as a location map in Fig. 2. Study area was divided to four different regions according to their locations and containing garnet minerals.

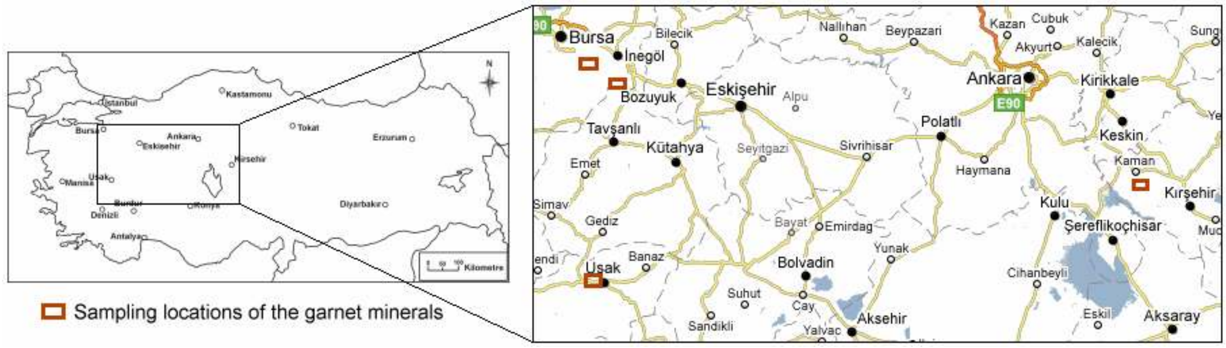

Fig. 2. Location map of the study area

Garnet samples were taken from these regions:

i) Bursa-Uludağ region
ii) Bursa-İnegöl region
iii) Kırşehir-Kaman region
iv) Uşak region

Bursa-Uludağ region garnets is located in an old wolfram mine district. In this region the thickness of the garnet-skarn zone is in between 2-35 m and mean thickness is seem to be approximately 12 m (Fig. 3). This zone is noticed with its dark brown colored view. Garnet mineral is the main component of this zone, there are also quartz, pyroxene, magnetite, pyrite, calcite and epidote minerals observed.

Fig 3. A view of garnet mineralization zone in Bursa-Uludağ region

Although the garnet mineral was characterized as grossularite-andradite in some researches [12, 13] it was observed as grossularite-andradite-spessartite solid solution in subsequent X-ray diffraction and chemical analysis. In this research, two different garnet samples (Fig. 4) were taken from Bursa-Uludağ region according to their different macroscopic view, and processed as individually.

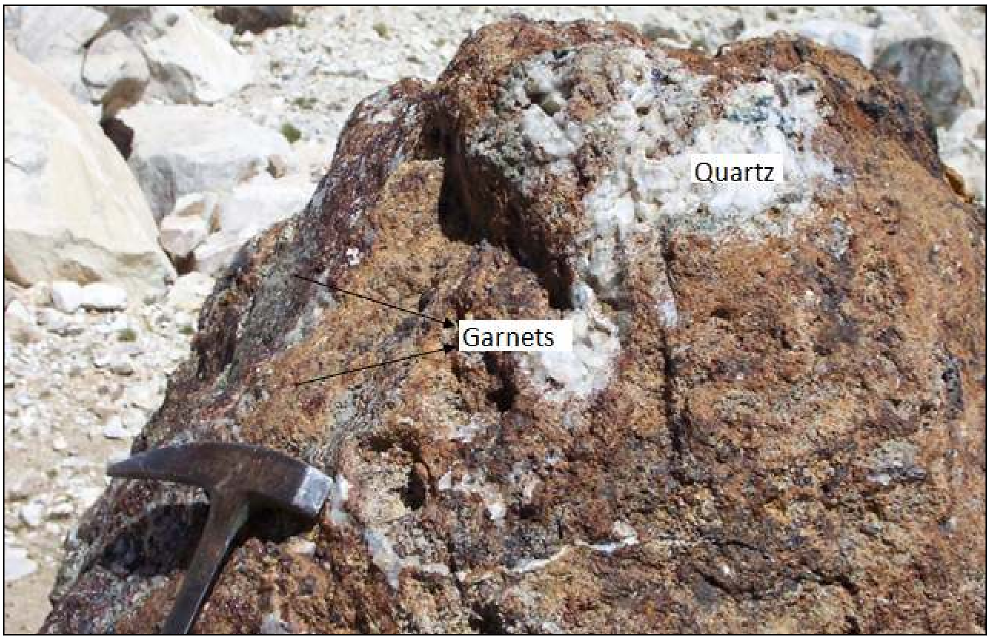

Fig. 4. A view of the Bursa-Uludağ region garnets

Bursa-İnegöl garnets exists in granite-marble contact zone, and the thickness of this zone is changing from 2 m to 25 m, in some part of this zone garnet content can reach 50-60 % percentage.

Kırşehir-Kaman region garnet minerals exist as crystal shaped in a mineralization zone having approximately 1-3 m thickness and 2 km length in marble and calc-silicatic marbles. Garnet crystals forming 30-50 % of the rock in this zone are found to be reached from several millimeters to 3-4 centimeters in diameter as dispersed in these calc-silicatic type rocks. In some part of this zone garnet crystals are observed as exposed off from worn mother rock because of its high abrasive strength (Fig.5).

Fig. 5. Kırşehir-Kaman region garnets which can be seen at the surface of calc-silicatic mother rock

Tokay and Bayramgil (1947) stated that northern metamorphites of Uşak consist of garnet schists having hornblende, biotite, muscovite, pyroxene and cassiterite [14]. Under this zone, coarse grained gneiss rock takes place in the field. There are two zones which were enriched by garnet minerals in the mica schists located over the garnet-schist rock unit. These vein shaped garnet levels have 2 m thickness and 50 % percentage of garnet mineral and also show continuity in the field (Fig. 6).

Fig. 6. Garnet vein located in the mica schists in the Uşak region

These garnet zones are marked with its dark grey and brown color in the field and garnet minerals are exist in this zone as porphyroblasts having 3 cm diameter. Biotite and muscovite minerals are covering these garnet porphyroblasts.

2.2. Mineralogical, Chemical and Physical Properties of Garnet Samples

XRF (X Ray Flouresan) method was used for quantitative analyzing of garnet samples. Chemical composition of these samples is given in Table 1. Chemical composition of the commercial Indian garnet was taken from the company's technical data sheet. Mineralogical compositions of samples were determined by XRD analysis method. Densities of the samples are very important physical property in terms of AWJ cutting performance that's why were determined by picnometer. In addition, loose package density and hardness of the samples were also determined.

When the chemical compositions and XRD patterns of the samples were analyzed; Uludağ-1 and Uludağ-2 samples were observed to be a solid solution of grossularite-andradite-spessartite in varied concentrations, Kaman sample was observed to be a solid solution of grossularite-andradite, Uşak sample was observed to be a solid solution of almandine-andradite. Commercial Indian origin garnet which is already used in the AWJ cutting plant was also analyzed and mineral composition was determined as almandine.

Table 1. Chemical compositions of the garnet samples

	Region					
	Uludağ-1	**Uludağ-2**	**İnegöl**	**Uşak**	**Kaman**	**C. Garnet**
SiO_2	36.65	35.56	34.6	38.40	36.21	38.62
Al_2O_3	10.73	14.16	1.54	18.98	13.88	22.76
Fe_2O_3	14.48	10.64	31.6	31.75	7.30	29.32
CaO	26.00	29.66	27.6	5.43	33.04	1.94
MnO	6.869	4.867	1.40	0.417	0.187	4.87
MgO	0.37	0.04	0.95	1.93	0.55	0.98
Na_2O	0.21	0.17	0.04	0.12	0.19	0.12
K_2O	0.08	0.03	0.08	0.09	0.01	0.01
TiO_2	0.06	0.06	0.06	0.74	0.92	0.46
P_2O_5	0.03	0.05	0.06	0.10	0.02	0.01
LOI	1.60	0.87	1.44	0.46	0.56	0.23
Total	95.04	94.90	99.37	97.70	91.94	99.32

Mineral compositions of the samples were determined by XRD method, and their XRD patterns are given in Fig. 7.

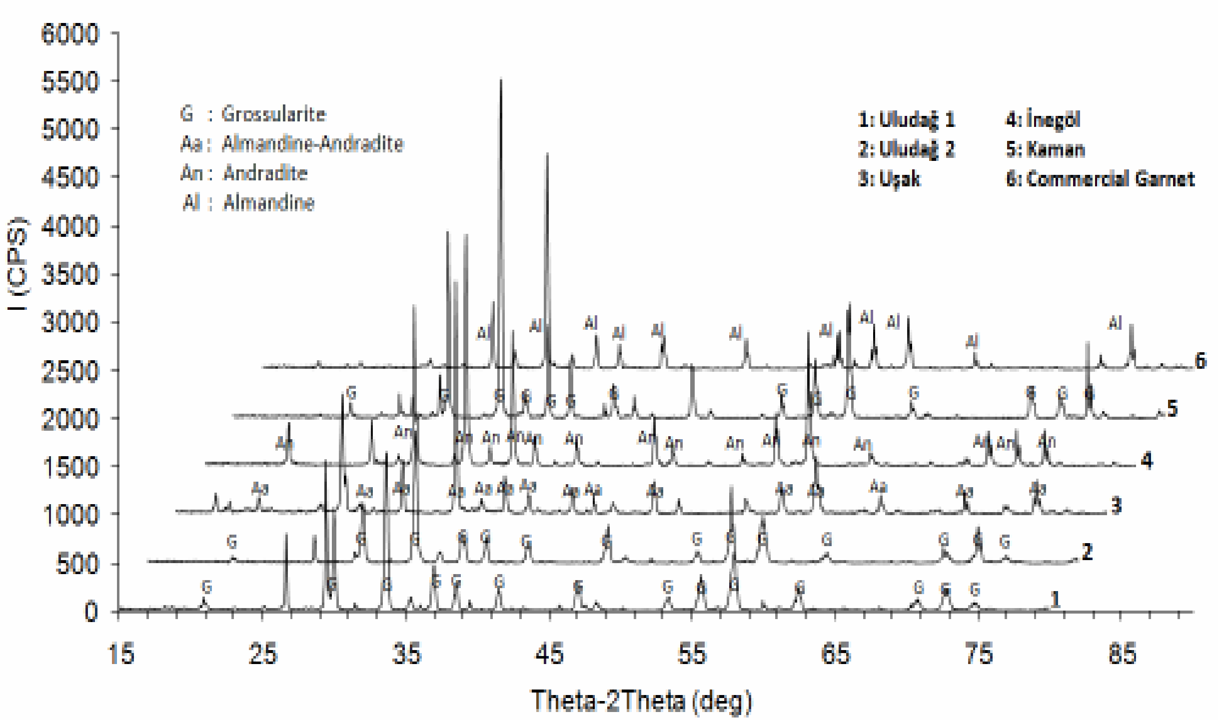

Fig. 7 XRD patterns and mineral compositions of the garnet samples

Hardness, density, bulk density for 80 mesh of the samples were also investigated and their values are given in Table 2. Because of the composition of the garnet samples taken from the study areas having different mineralogical composition from the commercial almandine garnet, their hardness and density values are observed as lower.

Table 2. Some physical properties of garnet samples

Samples	Hardness (Mohs)	Density (g/cm^3)	Bulk density (g/cm^3)
Uludağ-1	7-7,5	3,72	1,97
Uludağ-2	7-7,5	3,68	2,03
İnegöl	6,5-7	3,67	1.85
Uşak	7-7,5	3,79	2.00
Kaman	7-7,5	3,57	1.87
Commercial Garnet	7,5-8	4,11	2,42

2.3. Preparation of the Garnet Samples as Abrasive Medium

AWJ cutting applications include two steps; one is preparation of the garnet samples as an abrasive medium used in AWJ cutting operations, and the second is trial of these abrasive samples in cutting of different materials by AWJ in a plant.

Garnet samples taken from the study area were prepared as having 80 mesh particle size. For this purpose, garnet samples were first crushed by a jaw crusher than passed through a roll crusher to reach desired particle size. Crushed garnet samples were washed, screened and thus fines were removed and desired particle size distribution was obtained. Sized garnet samples were passed through a dry magnetic separator to remove some possible non-magnetic impurities such as quartz, calcite, and etc. by using magnetic feature of garnet mineral.

Shape of the garnet particles taken from the prepared samples were investigated by Scanning Electron Microscope (SEM) technique. SEM photographs are given in Fig 8-13.

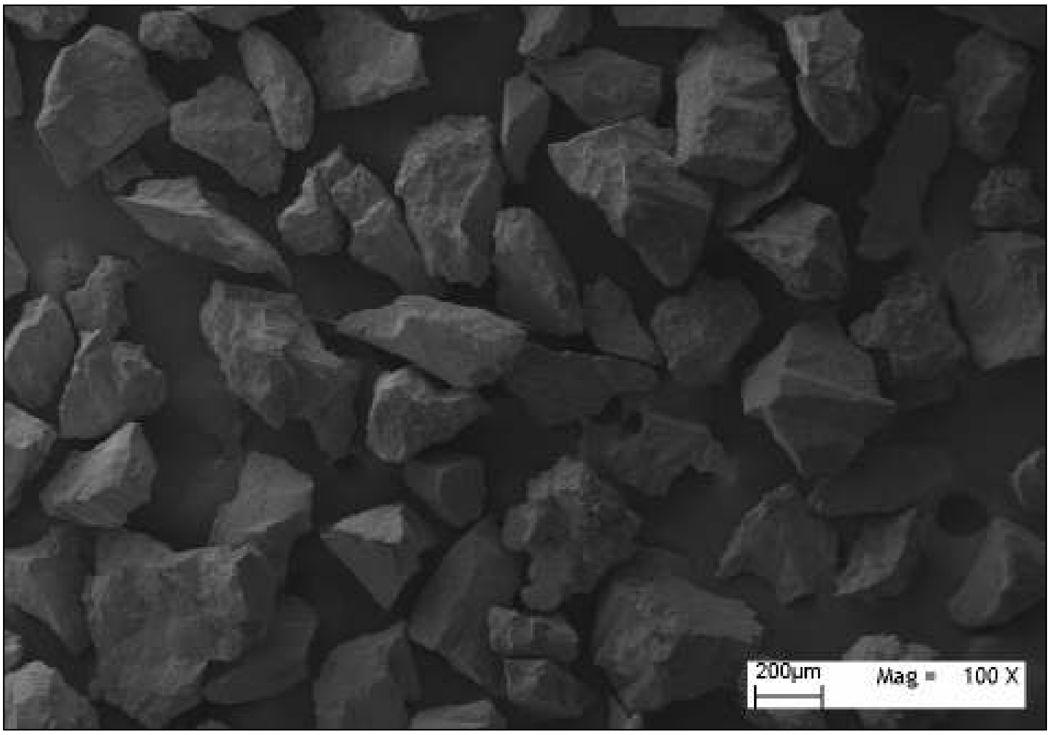

Fig. 8. SEM view of the Uludağ 1 garnet sample

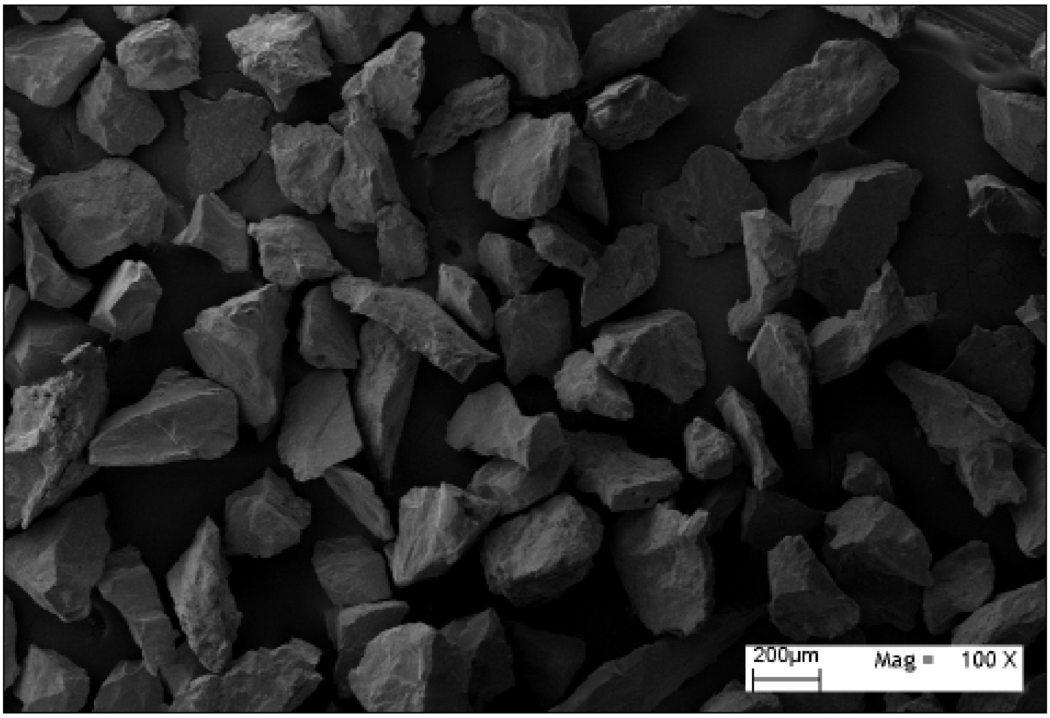

Fig. 9. SEM view of Uludağ 2 garnet sample

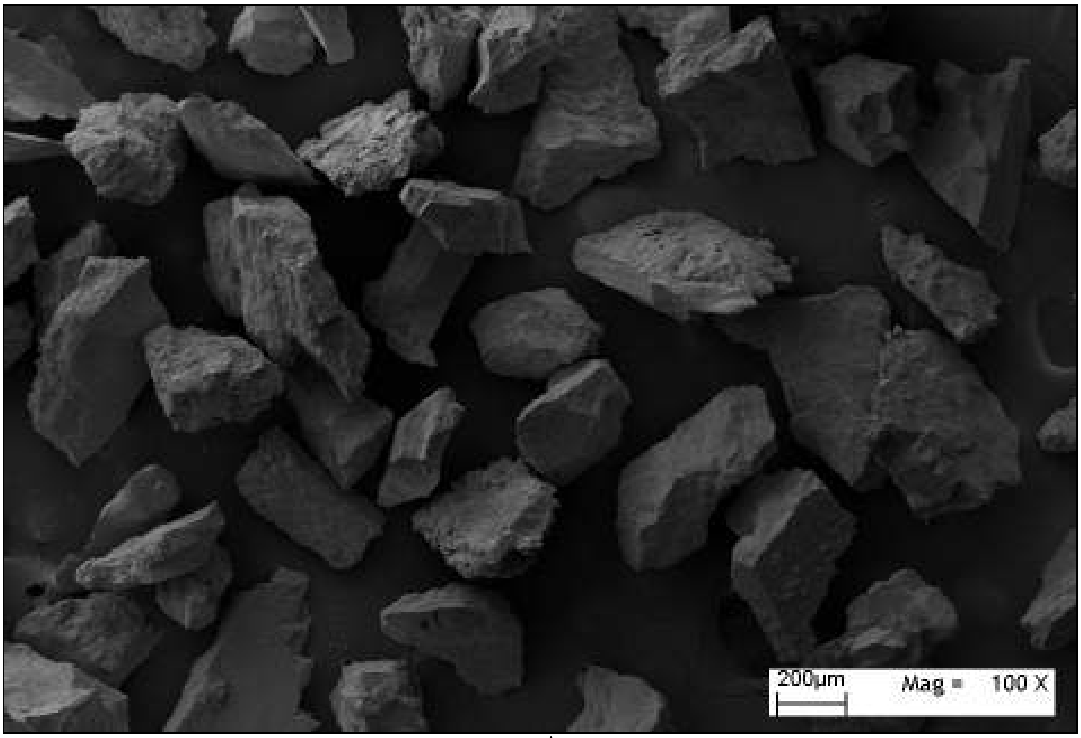

Fig. 10. SEM view of İnegöl garnet sample

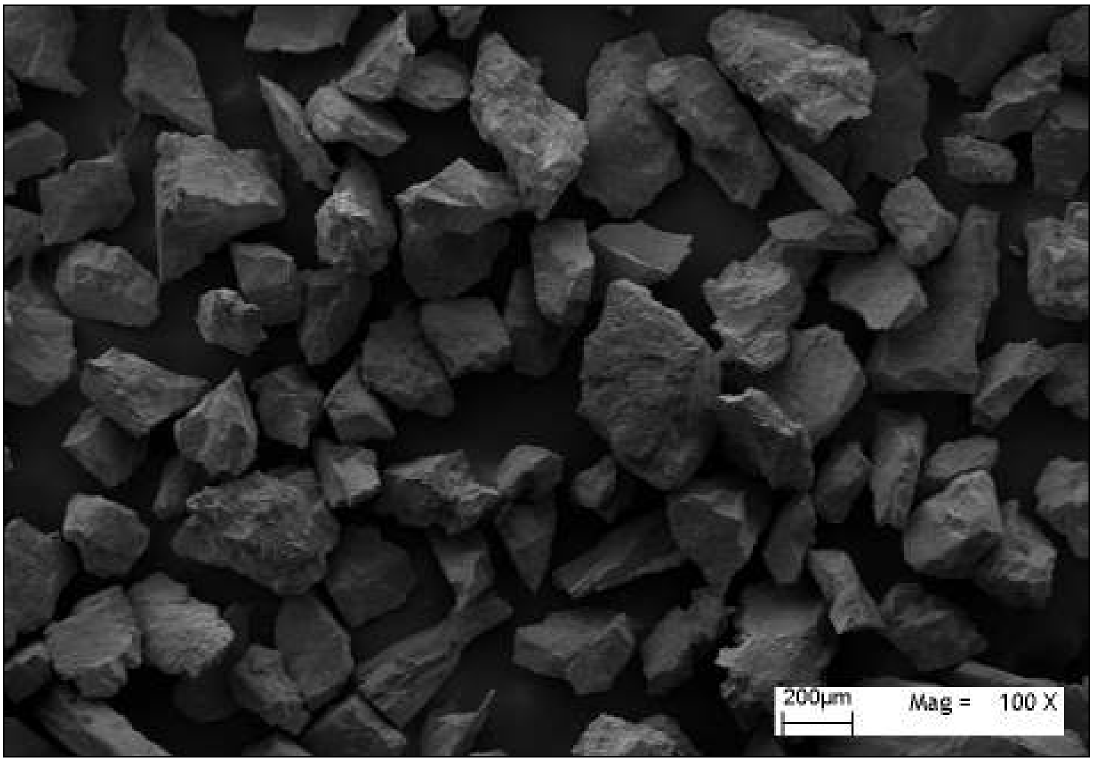

Fig. 11. SEM view of Uşak garnet sample

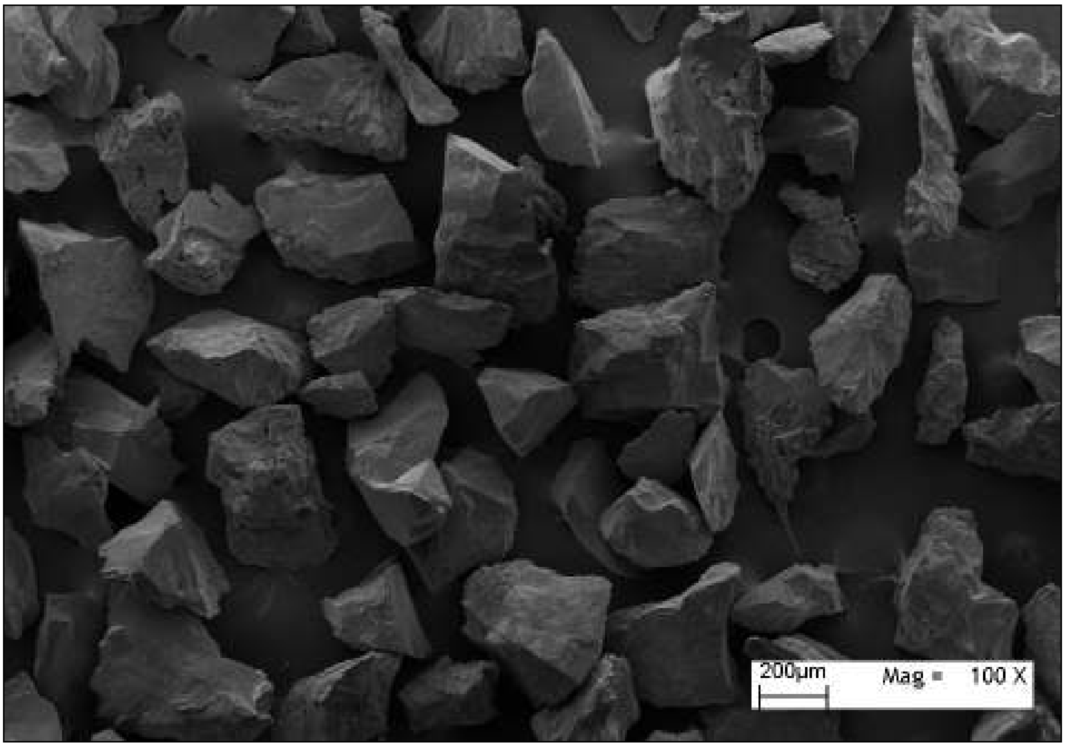

Fig. 12. SEM view of Kaman garnet sample

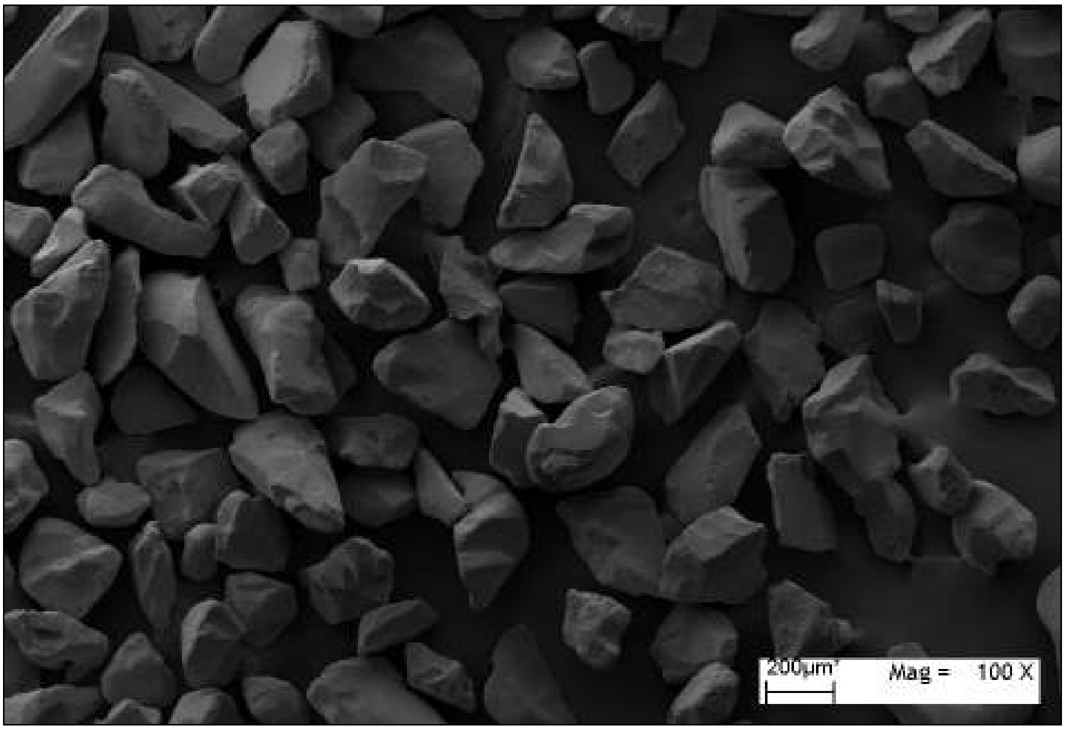

Fig. 13. SEM view of commercial almandine garnet sample

Prepared garnet samples are very similar as seen in the figures; they have sharp edges and sub-circular shape because of their crystallization structure and also crushing operations. Commercial almandine garnet particles show a different and characteristic shape having rounded edges and more circular than the others as seen in Fig. 13. This caused by the formation of the garnet particles in alluvial deposits such as river beds, where it has been smoothed by the constant running water.

2.4. AWJ cutting applications

In this research, Afyon White marble, Rosa Porrino granite, standard ST 37 steel, standard 5083 aluminum materials having 2 cm thickness and 10 cm width were cut by using these prepared garnet abrasive samples in AWJ cutting system.

Constant machine and operating parameters were chosen as following; orifice/focusing tube having 0.25 mm / 1.1 mm diameter; focusing tube length having 80 mm, working pressure having 350 MPa, power of the pump having 37 kW.

According to the previous cutting experiences abrasive feed rate was selected as 350 g/min. Cutting rate was selected as 350 mm/min for marble, 300 mm/min for granite, 110 mm/min for aluminum, 35 mm/min for steel as different. These abrasive feed rate and cutting rate values were performed for every garnet samples. Thus, only the effect of the garnet samples on the AWJ cutting operation and also their performance were investigated.

2.5. Determination of the Quality of the Cut Surfaces

Marble, granite, steel and aluminum materials were cut by AWJ cutting system in which the garnet samples were used. Cut surfaces of these materials were investigated by a stylus type Mitutoyo Surftest SJ-401 surface roughness measurement device, and surface profiles and also roughness properties of the surfaces were determined. Surface roughness measurement setup is given in Fig.14, and a roughness profile is given in Fig.15 for steel cut by Kaman garnets as an example.

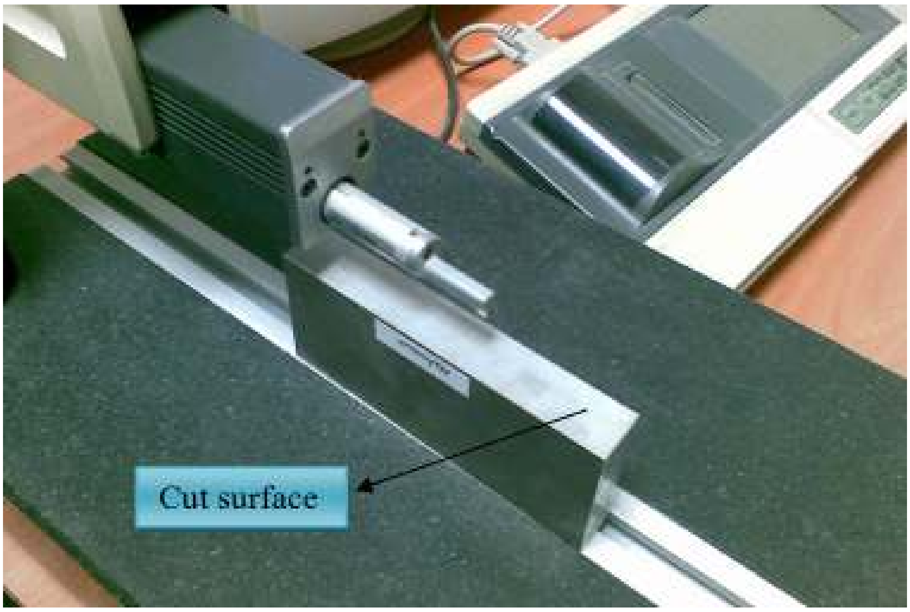

Fig. 14. Stylus type surface roughness measurement device setup

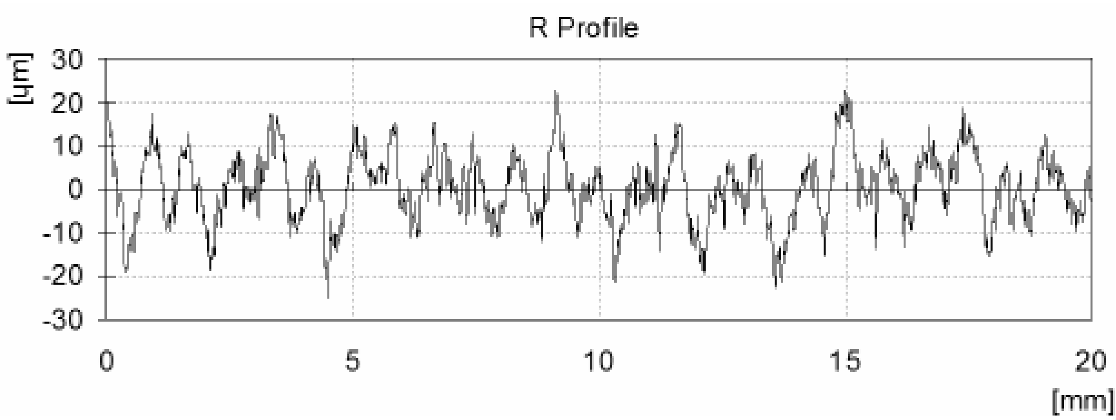

Fig. 15. Surface roughness profile for steel material cut by Kaman garnets

Ra (arithmetical mean roughness) and Rz (ten-point mean roughness) roughness parameters were measured for every material cut by different garnet samples, average values are given in Table 3.

Table 3. Average values of Ra and Rz roughness parameters of the materials cut by different garnet samples

Materials	Marble		Granite		Aluminum		Steel	
Garnet Types	Ra	Rz	Ra	Rz	Ra	Rz	Ra	Rz
Uludağ-1	16.52	109.8	43.83	208.6	13.26	92.60	4.87	45.20
Uludağ-2	15.62	106.9	29.62	133.1	13.45	83.80	7.98	49.50
Kaman	16.30	102.5	20.47	116.4	12.64	84.10	6.34	42.00
Uşak	17.53	115.4	11.57	68.3	12.92	83.50	9.15	59.70
İnegöl	12.35	89.9	36.23	193.6	13.10	98.90	6.51	45.10
Commercial	16.39	105.0	45.29	241.8	5.98	70.80	6.41	49.60

The difference between the roughness values of different materials is not the key point, because this is related with cutting speed and if it is changed roughness values for the given materials will be changed. But, the difference between the roughness values of same materials cut by different garnet samples is important, because this difference show the cutting performance of the garnet samples.

3. RESULTS AND DISCUSSION

In this research, five different garnet samples taken from various locations of Turkey were investigated to be used as an abrasive medium in AWJ cutting applications. Indian based commercial almandine type garnet abrasive was also used in cutting operations and also taken as a control material in determining the cutting performance. Investigation on the cut surfaces by visual inspection and roughness measurement showed that other type of garnet minerals can be used for this purposes.

Compositions of the garnet samples are a mixture of grossularite, andradite, spessartite and a little almandine minerals in various ratios. According to their mineralogical composition, İnegöl, Uludağ and Kaman samples has lower density and hardness values than the Uşak and commercial almandine samples. Abrasive flow rate was selected as 350g/min according to the orifice/nozzle combination and the materials to be cut. For a definite target material such as granite, different garnet samples were used as same mass flow rate at the same cutting rate to determine only the effect of the morphologic, physical and mechanical properties of the garnet samples on cutting operations. But, at the same time volumetric abrasive flow rate will be different from each other because of their different densities. This will cause 10-15% more volumetric usage for the garnet samples having less density in comparison to almandine garnets. From the point of abrasive costs for operators it won't bring additional cost since the price of the garnet is determined as tonnage.
The wear effect of the garnets used in this research on the nozzles/focusing tubes has to be investigated in further studies. An increase in the volumetric usage of the abrasive may increase the wear of the nozzles.

It is known that there are many garnet resources in metamorphic massifs in Turkey and also in other countries, and evaluating these garnets for this purpose and economical analysis have to be carry out.

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