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Article

Research into the disintegration of abrasive materials in the abrasive water jet machining process

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Abstract: The size and distribution of abrasive particles have a significant influence on the effectiveness of the cutting process by the high-speed abrasive water jet (AWJ). The paper deal with the abrasive materials disintegration intensity in AWJ cutting during the creation of the abrasive jet. An evaluation of the abrasive materials grabbed after forming in the cutting head was carried out and its grain distribution was evaluated. Used here the arithmetic, geometric and logarithmic method of moments and Folk and Ward method. The influence of abrasive concentration of abrasive materials as alluvial garnet, recycled garnet, corundum, and olivine on grain distribution was studied. A recovery analysis was also carried out and the recycling coefficient for each tested abrasive material was determined.

Keywords: abrasive materials; garnet; corundum; olivine; disintegration, cutting process efficiency

1. Introduction

The size and shape of the abrasive grains [1], [2] are important in abrasive machining processes due to the achievement of both high efficiency and high accuracy [3], [4], [5] of the treated surface. During the injection of abrasive into jet within the mixing chamber and the focusing tube of the cutting head, follows the intensive abrasive material disintegration [6]. It is one of the characteristic properties of this process [7]. Because abrasive grain size distribution is essential in effectiveness in most abrasive cutting process [8], [9], especially in AWJ [10], it seems advisable to carry out detailed research in this aspect for achievement the maximal efficiency.

The other factor in favor of undertaking such research is cost effectiveness. The cost of most often garnet abrasive materials, is up to 60% of the total cost of AWJ technology [11], results in its limited use in material cutting operations. The high cost of garnet abrasives to other constituents (Fig. 1) is effect of the relatively high price of garnets from India, Australia, and USA.

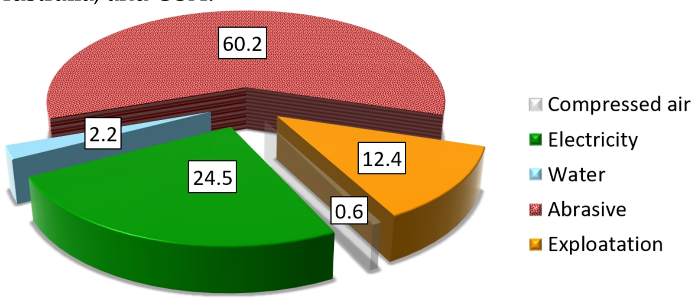

Figure 1. Exemplary percentage cutting costs for the Omax 55100 machining center without amortization costs. Media use: garnet abrasive 24 kg/h, electrical energy 30 kWh, water 270 dm³/h, compressed air 300 dm³/h [11].

Another way to reduce machining costs is recycling of the used abrasive. Among the abrasives, especially alluvial garnet, the recovered abrasive turns out to be more effective

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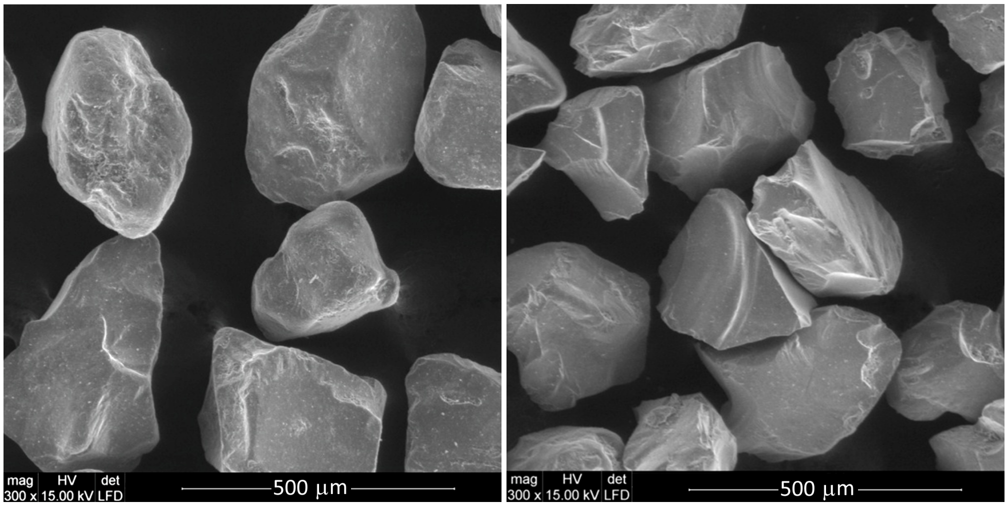
as the cutting edges are sharper (Fig. 2). Additionally, recycling of the abrasive materials can performs the abrasive water jet technique more saving, effective, and environmentally friendly [12]. For these reasons, research on the recycling of abrasives, especially garnet, is the subject of research in various scientific centers.



(a) (b)

Figure 2. Exemplary view of garnet abrasive material: a) fresh, before AWJM process, b) recycled after AWJM process. Magnification 300 x.

Chetty et al. [13] published the results of regional garnet abrasives recycling in cutting aluminum process by abrasive water jet. The impact of pressure, traverse speed, and abrasive flow rate on grain size, depth of cut, width, and taper of the cut kerf. Recycled abrasives reduce kerf taper, improving the parallelism of cut surface. These effects show that the appropriate selection of abrasive grain size distribution is essential for reaching better results.

The determination of an extent of changes in the size of particles induced in the cutting head published Hlavac et al. [14]. They recognized of the grain size information at the cutting head output is essential for examine of the further processes, e.g., the impingement of water stream with industrial mineral particles on a solid-state object or impact of such water stream with fluid barrier or reverse flow of the same type.

Aydin [15] presented the study of rock properties affecting on the recycling of abrasives in AWJ cutting are investigated. Abrasive mass percentage above 106 µm was considered as a performance criterion in terms of recycling of abrasives since these abrasives can be effectively reused in the rock cutting applications. The study reveals that a substantial quantity of used abrasives particles is in a reusable condition.

Cutting efficiency of multiple recycling garnet abrasive materials [16] was also tested in effects in cutting depth, kerf width, kerf taper angle and surface roughness. After each pass the grabbed abrasive particles were dried and sieved for determination of their disintegration behaviors. The garnet grains smaller than 106 µm were rejected. Substantial number of used abrasives can be qualified to reused in the cutting. The recycling factor of abrasives are determined from over 81% after the first pass to over 17% fourth pass, properly.

Gye-Chun Cho et al. [17] carried out the rock cutting research with different grain size garnets to find the influence of its flow rate, physical characteristic, and grain size distribution on rock cutting efficiency. Additionally, garnet grain disintegration was tested for the abrasive water jet. The test results demonstrate that the grain size distribution, garnet purity, density, and hardness are the most important factors for rock cutting

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efficiency. The research presents better comprehension of coarse garnet effectiveness aptly to the garnet characteristics.

The feasibility study of abrasive materials usage under a 400 MPa AWJ presented Perec [18]. Tested a garnet, ilmenite and olivine abrasives and showed preliminary results on disintegration these abrasive materials in the cutting head. Substantial importance is the growth in cutting capacity with crushed grains by the emergence of new ones cutting edges. Ground on the study showed results on difference in machining efficiency and presented wear of the focusing tube - the key element formatting of the jet. Besides to the work aimed at reducing the grinding of the abrasive grains, conducted the research on using a water jet for disintegration of mineral materials [19], [20], [21]. The impact of an internal shape of the mixing chamber on the particle comminution in the process with water stream was researched experimentally with a connection with the reverse jet disintegration of materials [22].

2. Materials and Methods

Abrasive grains utilized in AWJ cutting systems are one of the most significant influence on the cutting kerf properties. The most used abrasive material is mineral garnet. Its wide use in the high-pressure water jet as the abrasive material is reasoned by attaining high efficiency at comparatively slight the focusing tube durability [23]. Alternative natural and synthetic abrasives, such as aluminum oxide [24] or olivine [25], and may also be used. In the case of cutting with an abrasive suspension water jet (ASWJ), quartz sand as abrasive material can be used [26]. To carry out a compromise between focusing nozzle long life and the big efficiency of machining, the heedful selection of abrasive material is endorsed [27].

2.1. Alluvial garnet

Australian garnet used in the research is mined from an alluvial deposit near Geraldton in Western Australia by GMA Garnet company. The Australian garnet has an extremely low dust level and advanced processing methods guarantee a low chloride content. Rinsing with spring water is used to reduce soluble salts to less than 10 ppm, and roasting is used to burn off any organic matter. Double screening is used to ensure an adequate grain distribution. Its detailed properties are presented in the Table 1.

Table 1. Detailed properties of Australian alluvial garnet [28].

Properties	Units	Value
Chemical composition		
$Fe_3Al_2(SiO_4)_3$	%	>97.0
$FeTiO_3$	%	<2.0
$CaCO_3$	%	<1.00
$ZrSiO_4$	%	<0.10
SiO_2	%	<0.10
Melting point	^{o} C	1250
Density	kg/m^3	4100
Bulk Density	kg/m^3	2300
Hardness	Mohs	7.5-8.0

2.2. Recycled garnet

This abrasive is a recycling product of alluvial garnet, manufactured by GMA Garnet (Middle East) FZE in Jebel Ali Dubai, United Arab Emirates. The GMA Garnet abrasive can be recycled up to five times without compromising on performance [29]. Some increase in cutting efficiency is possible when using recycled abrasive. This is primarily due to good abrasion resistance and low brittleness. Recycling provides garnet users with

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a cost-effective and environmentally sound opportunity to dispose of used abrasive that would otherwise be collected as industrial waste.

2.3. Corundum

Corundum is a crystalline form of aluminum oxide (Al_2O_3). Among natural abrasives, only diamond is harder. It does not react with acids and most basic environments. Deposits of corundum occurs in contact with metamorphic rocks (emery) and gemstones (sapphire, ruby). The most popular forms of corundum are translucent corundum and emerald corundum. It is described by high hardness, good strength, and shape. Tools made of this abrasive material are suitable for grinding metals with high tensile strength, such as: carbon steel, general-purpose alloy steel, annealed malleable cast iron and hard melt etc. It can also be used as a refractory material. It is also widely used in the constructional production of coated abrasive tools, used especially for metal grinding.

The corundum used in the research, (fused alumina) was produced by Dengfeng Sweet Abrasives Co., Ltd. based in Dengfeng City, Zhengzhou, Henan, China. Its properties are presented in Table 2.

Table 2. Detailed properties of corundum [30]

Properties	Units	Value
Chemical composition		
Al_2O_3	%	94.5-95.5
SiO_2	%	1.33-1.50
Fe_2O_3	%	0.18-0.30
Ti_2O	%	2.45-3.50
CaO	%	0,11-0,30
Melting point	^{o} C	2050
Density	kg/m^3	3900
Hardness	Mohs	9.0

2.4. Olivine

Olivine is in fact the name of an isomorphic series of minerals lying between two extreme elements: fayalite and forsterite. Fayalite is a pure iron compound of Fe_2SiO_4, while forsterite is a pure magnesium compound of Mg_2SiO_4.

Green Lightning olivine, produced by SIBELCO NORDIC AS in Rud, Norway, from a deposit on the west coast of Norway, south of Ålesund, was used in the research. Green Lightning Olivine is a magnesium iron silicate with the highest magnesium content. Green Lightning is made from “Dunite rock” and does not contain free silica. Properties of olivine used in the research are presented in the Table 3.

Table 3. Detailed properties of Norwegian olivine [31].

Properties	Units	Value
Chemical composition		
MgO	%	48.8 – 49.7
SiO_2	%	41.5 - 41.9
Fe_2O_3	%	7.3 - 7.6
Al_2O_3	%	0.4 - 0.5
Cr_2O_3	%	0.31 - 0.66
Density	kg/m^3	3300
Bulk Density	kg/m^3	1700
Hardness	Mohs	6.5 - 7.0

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2.5. Apparatus and method

The main devices used in the test was a KMT Intensifier type I50 and CNC table type ILS55 by Techni Waterjet with dedicated PC control system.

To grab abrasive material after its escape from the cutting head, the unique catcher was designed and used. The receiver performs the function collecting and to preventing the abrasive materials farther disintegration after output the cutting head. The bottom PVC catcher was shielded by a hard metal plate to avert its perforation.

Research was conducted under pressure of 390 MPa at 0.25 mm ID water nozzle and 0.76 mm ID focusing tube. A variable control parameter was the concentration of abrasive in the jet. The following values were adopted for the tests: 15%, 17.5%, 20%, 22.5% and 25%.

For evaluation of the grain distribution of the abrasive materials, Retsch screening equipment was utilized. Mass of abrasive materials left on the screens was weighed on the digital lab scales. The statistics of the abrasive materials grains distribution of was performed using the Gradistat v.9.1 program [32] grounded on the Folk & Ward method [33].

3. Results and discussion

3.1. Abrasive grain disintegration

3.1.1. Alluvial Garnet

The impacts of the alluvial garnet abrasive disintegration in the cutting head during jet formation presents the Fig. 3. The distribution fresh grains is unimodal and symmetrical (Table 4). Skewness is near zero. Distribution is mesokurtic ($0.9<K_G<1.11$).

After leaving the cutting head at 15% concentration, density function of distribution shift to bimodal and asymmetrical (very fine skewed), with minus asymmetry. Skewness equal -0.304. Kurtosis is $0.67<K_G<0.9$ and distribution is platykurtic.

Increasing the concentration value to 17.5% results in a change of density function of distribution to the trimodal and asymmetrical (fine skewed), with negative asymmetry. Skewness is -0.285. Distribution is too platykurtic because kurtosis $0.67<K_G<0.9$.

Further increasing the concentration to 20% maintains distribution and skewness. Increasing the concentration over 22.5% leads to the achievement of very platykurtic distribution, because kurtosis $K_G<0.67$. Density function of distribution remains unchanged (trimodal and asymmetrical, fine skewed), with minus asymmetry.

For all concentration values the frequency of grains from 425 to 250 μm reduced drastically and appeared the superiority of the grains below 53 μm, which earlier was not occur [34].

Table 4. Alluvial garnet grains distribution statistics

Concentration [%]		**fresh**	**15**	**17.5**	**20**	**22.5**	**25**
Folk and Ward Method (μm)	MEAN	244.6	113.9	112.9	110.8	106.2	103.1
	SORTING	1.273	1.907	1.920	1.901	1.891	1.899
	SKEWNESS	-0.039	-0.304	-0.285	-0.259	-0.212	-0.121
	KURTOSIS	0.920	0.719	0.676	0.678	0.634	0.604
Folk and Ward Method (ϕ)	MEAN	2.032	3.134	3.147	3.174	3.235	3.278
	SORTING	0.348	0.931	0.941	0.927	0.919	0.925
	SKEWNESS	0.039	0.304	0.285	0.259	0.212	0.121
	KURTOSIS	0.920	0.719	0.676	0.678	0.634	0.604

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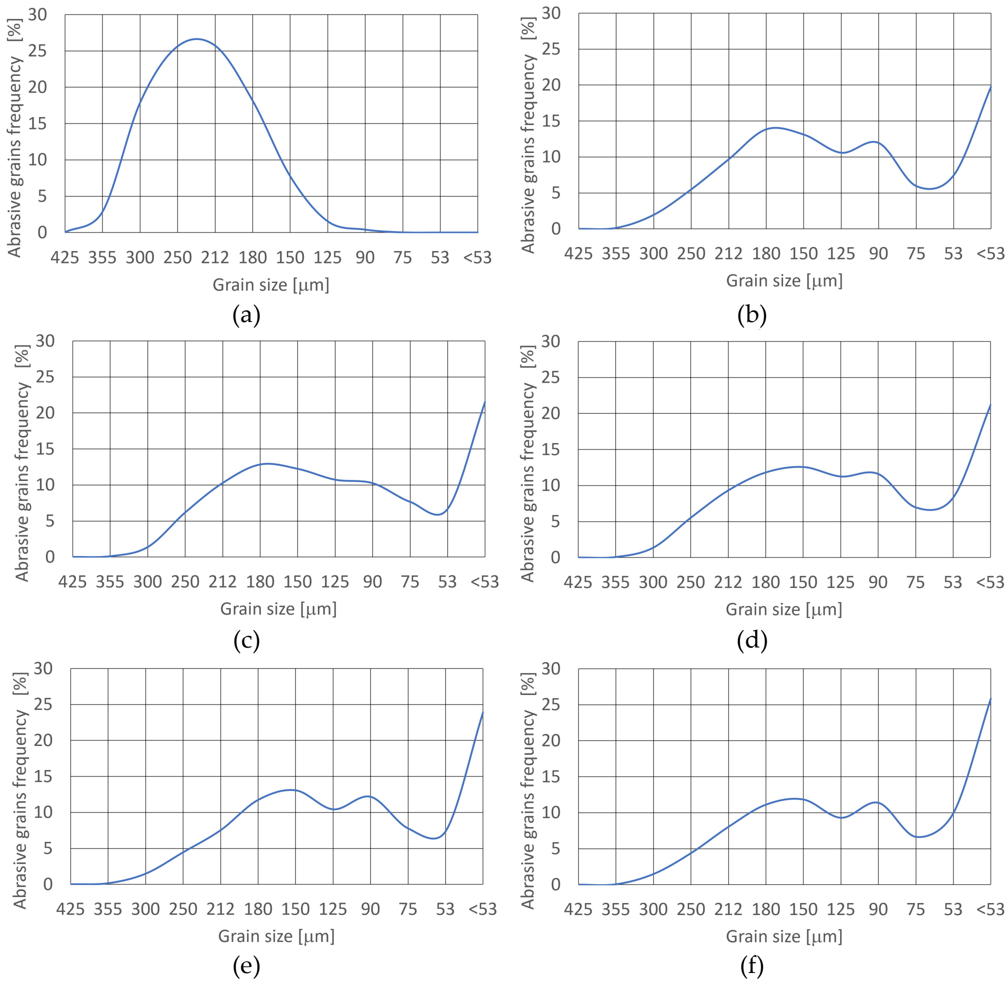

Figure 3. Size distribution of alluvial garnet grain at concentration(**a**) fresh, (**b**) 15%, (**c**) 17.5 %, (**d**) 20%, (**e**) 22.5%, (**f**) 25%.

3.1.2. Recycled Garnet

The outcomes of the recycled garnet abrasive disintegrated tests in the cutting head during jet formation presents the Fig. 4. The density function approximating the distribution fresh grains (Table 2) is bimodal and symmetrical (skewness is near zero). Distribution is platykurtic because kurtosis $0.67<K_G<0.9$.

After passing through the cutting head at 15% and 17.5% concentration, density function of distribution is still bimodal and asymmetric (fine skewed), with negative asymmetry. Skewness equal -0.272 to -0.298. Distribution is platykurtic because kurtosis $0.67 <K_G<0.9$.

Increasing the concentration value over to 20% results in a change of distribution to very platykurtic because kurtosis $K_G<0.67$. Density function of distribution keeps going bimodal and asymmetric (fine skewed), with negative asymmetry. Skewness is -0.285.

Further increasing the concentration to 25% effects in a change of density function of distribution to the trimodal and asymmetric (fine skewed), with negative asymmetry. Skewness equal -0.206. Distribution is too very platykurtic because kurtosis $K_G<0.67$.

For each concentration value the frequency of grains from 425 to 250 μm decreased radically and seemed the dominance of the grains below 53 μm, which earlier was not occur.

Table 5. Recycled garnet grains distribution statistics

Concentration [%]		fresh	15	17.5	20	22.5	25
Folk and Ward Method (µm)	MEAN	246.4	114.7	119.2	112.9	110.0	113.5
	SORTING	1.315	1.964	2.007	1.972	1.971	2.005
	SKEWNESS	0.033	-0.272	-0.298	-0.252	-0.186	-0.206
	KURTOSIS	0.819	0.686	0.695	0.627	0.618	0.612
Folk and Ward Method (ϕ)	MEAN	2.021	3.124	3.069	3.146	3.185	3.139
	SORTING	0.395	0.974	1.005	0.980	0.979	1.004
	SKEWNESS	-0.033	0.272	0.298	0.252	0.186	0.206
	KURTOSIS	0.819	0.686	0.695	0.627	0.618	0.612

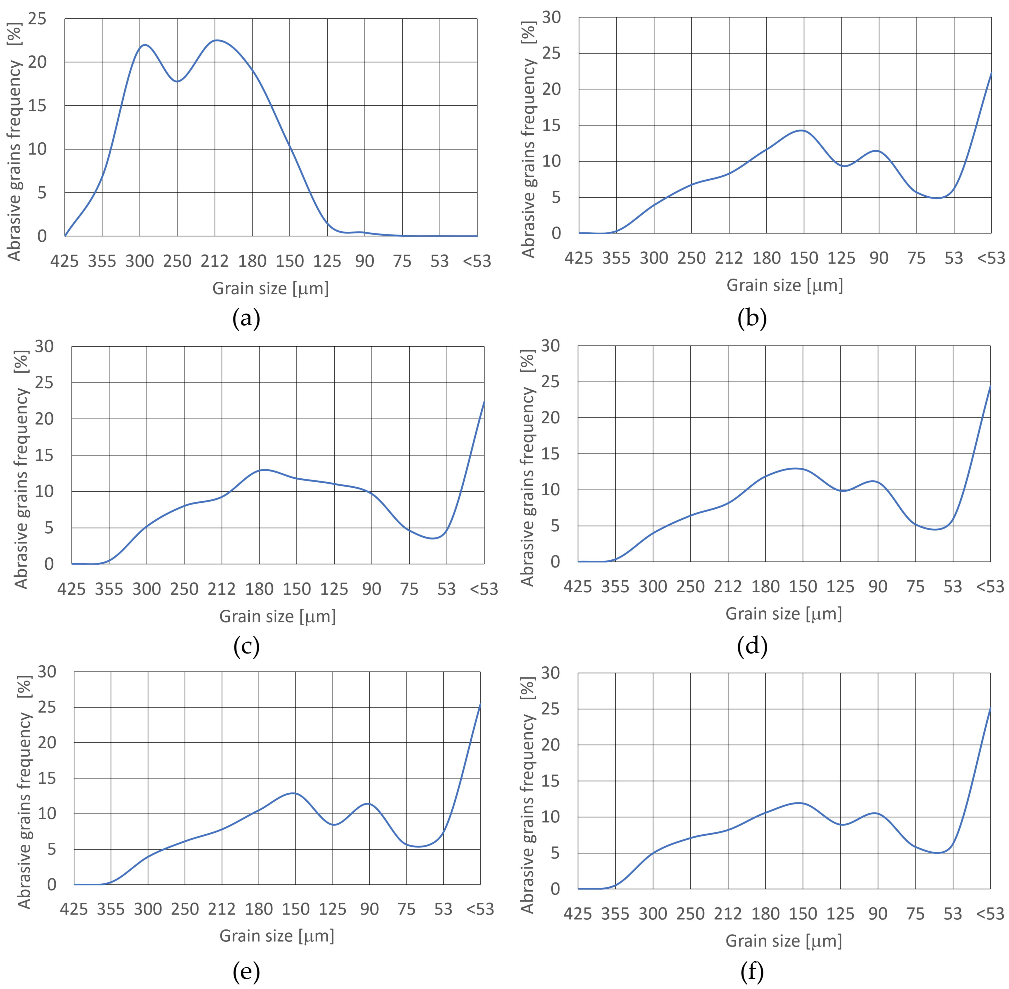

Figure 4. Size distribution of recycled garnet grain at concentration: (**a**) fresh, (**b**) 15%, (**c**) 17.5 %, (**d**) 20%, (**e**) 22.5%, (**f**) 25%.

3.1.3. Corundum

The effects of corundum abrasive disintegration in the cutting head through jet formation presents the Fig. 5. The density function approaching the distribution fresh grains is unimodal and symmetrical (Table 6) since skewness is near zero. Distribution is mesokurtic ($0.9<K_G<1.11$).

Table 6. Corundum grains distribution statistics

Concentration [%]		**fresh**	**15**	**17.5**	**20**	**22.5**	**25**
Folk and Ward Method (μm)	MEAN	194.8	92.82	90.33	89.76	90.83	95.77
	SORTING	1.163	1.741	1.730	1.720	1.721	1.746
	SKEWNESS	-0.067	-0.162	-0.109	-0.094	-0.155	-0.261
	KURTOSIS	1.004	0.573	0.577	0.570	0.579	0.575
Folk and Ward Method (ϕ)	MEAN	2.360	3.429	3.469	3.478	3.461	3.384
	SORTING	0.218	0.800	0.791	0.782	0.783	0.804
	SKEWNESS	0.067	0.162	0.109	0.094	0.155	0.261
	KURTOSIS	1.004	0.573	0.577	0.570	0.579	0.575

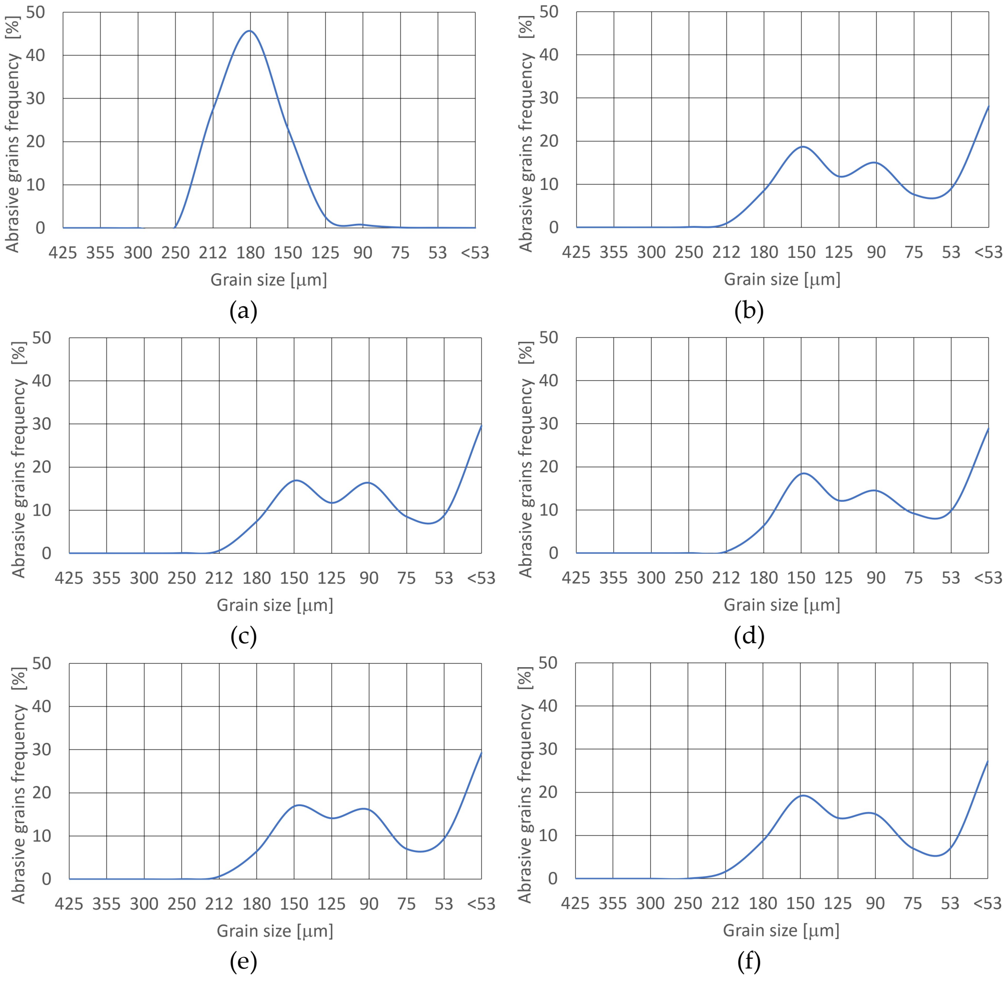

Figure 5. Size distribution of corundum grain at concentration: (**a**) fresh, (**b**) 15%, (**c**) 17.5 %, (**d**) 20%, (**e**) 22.5%, (**f**) 25%.

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After passing through the cutting head at 15% concentration, density function of distribution change to bimodal and asymmetric (fine skewed), with negative asymmetry. Skewness equal -0.162. Distribution is very platykurtic because kurtosis $K_G<0.67$.

Increasing the concentration value to 20% results in a change of density function of distribution to the trimodal and symmetrical. Skewness equal -0.094. Distribution is too very platykurtic because kurtosis $K_G<0.67$. Further increasing the concentration causes a return to bimodal and asymmetric (fine skewed), with negative asymmetry. Distribution remains very platykurtic because kurtosis $K_G<0.67$.

For all concentration abrasive grains in the jet, the frequency of grains from 212 to 180 µm decreased significantly and appeared the superiority of the grains below 53 µm, which was not happen previously.

3.1.4. Olivine

The effects of the study of olivine abrasive disintegrated in the cutting head at the period of jet formation show the Fig. 6. The density function approximating the distribution fresh grains is unimodal and fine skewed (Table 7) because skewness is -0.137. Distribution is mesokurtic (0.9<KG<1.11).

After passing through the cutting head at 15% concentration, density function of distribution shift to bimodal and asymmetric (fine skewed), with negative asymmetry. Skewness equal -0.104. Distribution is very platykurtic because kurtosis $K_G<0.67$.

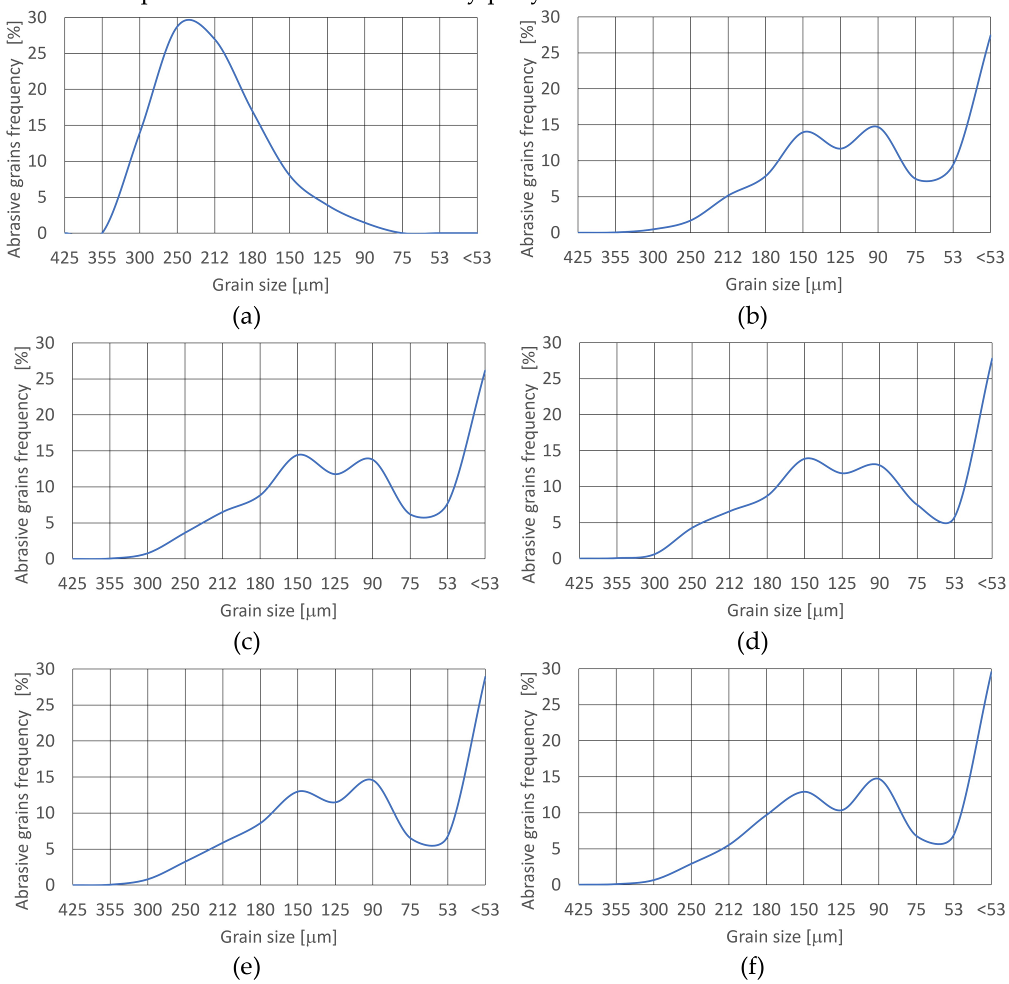

Figure 6. Size distribution of olivine grain at concentration: (**a**) fresh, (**b**) 15%, (**c**) 17.5 %, (**d**) 20%, (**e**) 22.5%, (**f**) 25%.

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For the 17.5% concentration, density function of distribution is still bimodal and asymmetric (fine skewed), with negative asymmetry. Skewness equal -0.272 to -0.298. Distribution is too very platykurtic.

After passing through the cutting head at 20% concentration, density function of distribution shift to trimodal. Asymmetric (fine skewed) character with negative asymmetry remains unchanged. Skewness equal -0.169. Distribution is very platykurtic (kurtosis K_G<0.67).

Further increasing the concentration to 22.5% and over effects in back to bimodal density function of distribution and leads to the keep of very platykurtic distribution, because kurtosis K_G<0.67 and fine skewness with negative asymmetry.

For all concentration abrasive in the jet, the frequency of grains from 300 to 212 µm decreased significantly and appeared the predominance of the grains below 53 µm, which previously was not occur.

Table 7. Olivine grains distribution statistics

Concentration [%]		fresh	15	17.5	20	22.5	25
Folk and Ward Method (µm)	MEAN	235.7	94.99	101.5	101.1	98.23	97.28
	SORTING	1.274	1.802	1.856	1.869	1.853	1.848
	SKEWNESS	-0.137	-0.104	-0.185	-0.169	-0.125	-0.102
	KURTOSIS	1.020	0.619	0.618	0.614	0.616	0.607
Folk and Ward Method (ϕ)	MEAN	2.085	3.396	3.300	3.306	3.348	3.362
	SORTING	0.349	0.850	0.892	0.902	0.889	0.886
	SKEWNESS	0.137	0.104	0.185	0.169	0.125	0.102
	KURTOSIS	1.020	0.619	0.618	0.614	0.616	0.607

3.2. Recycling of abrasive materials

After abrasive grabbing and drying, sieve analysis was executed, and the mass of each fractions was intended. For all tested abrasive size range is within the range of 350 to 125 µm. To establish what fraction of the original range is found in the jet formed in the cutting head, all of the fractions smaller than the lower limit of the particle distribution, were rejected as ineffective in the cutting process [12]. It is illustrated in Fig. 7. Details of abrasive material distribution presents Table 8.

Table 8. Recycled abrasives grains distribution statistics

Abrasive material		Alluvial garnet	Recycled garnet	Corundum	Olivine
Folk and Ward Method (µm)	MEAN	187.1	209.9	160.7	175.7
	SORTING	1.287	1.355	1.165	1.267
	SKEWNESS	0.071	0.098	0.029	0.181
	KURTOSIS	0.889	0.857	0.928	0.918
Folk and Ward Method (ϕ)	MEAN	2.418	2.252	2.638	2.509
	SORTING	0.364	0.438	0.221	0.341
	SKEWNESS	-0.071	-0.098	-0.029	-0.181
	KURTOSIS	0.889	0.857	0.928	0.918

In the recycling process of alluvial garnet, grains smaller than the limit (for grains # 80 it is 90 µm) was removed as inefficient during the cutting process [Perec, 2018]. The very small positive asymmetry density function approximating the grain distribution can be visible. Skewness is equal 0.071 and distribution is mesokurtic (0.9<K_G<1.11).

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In the case of recycled garnet, like alluvial garnet, grains smaller than the 90 μm was removed as ineffective in the cutting operations. The density function approaching the distribution is unimodal and almost symmetrical because skewness is close to zero. Kurtosis is in the range 0.67 <K_G<0.9, there the distribution is platykurtic.
For corundum recycled grains, the density function describing the distribution is unimodal and practically symmetrical (skewness is equal 0.029). Distribution is mesokurtic (0.9<K_G<1.11).
In the recycling of olivine grains, smaller than the limit (for grains #60 it is 125 μm) they were removed as unproductive in the cutting. The asymmetry (coarse skewed) density function approximating the recycled grain distribution is also visible.

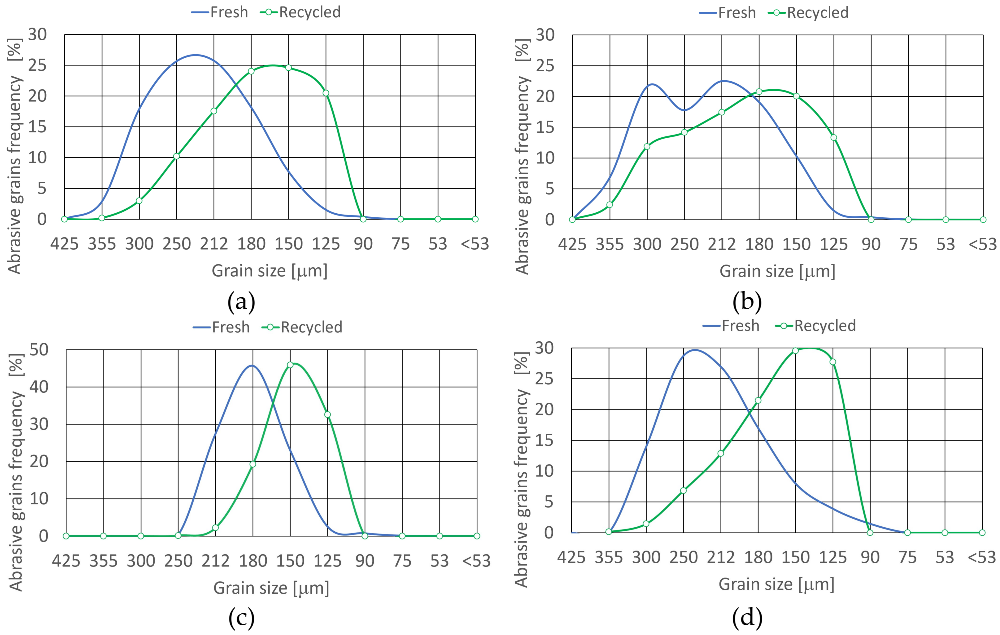

Figure 7. Size distribution of recycled abrasive materials: (**a**) alluvial garnet, (**b**) recycled garnet, (**c**) corundum, (**d**) olivine

The recycling rate was calculated on basis equation:

$$C_r = m_r / m_t \quad (2)$$

where:
C_r is abrasive recycling coefficient [g/g]
m_r is mass of recycled abrasive [g]
m_t is total mass of abrasive [g]

Specific results for tested abrasives are presented in Fig. 8. The recycling coefficient, amounting to 0.61 was observed for the recycled garnet.

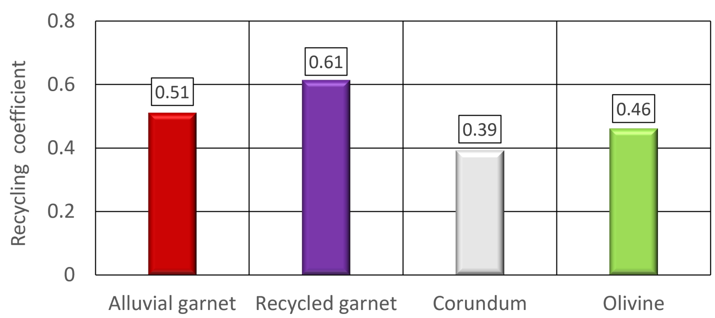

Figure 8. Recycled coefficient for tested abrasive materials

The second biggest value was noted for alluvial garnet. This implies it can be estimated that over half of the expended abrasive is possible to reuse.
The following abrasives were olivine, with the recycling coefficient equal to 0.46, and corundum with 0.39 the recycling coefficient. This means that over one-third of the abrasive can be used the second time.
In the case of corundum, apart from its lowest recycling rate, a major obstacle to its widespread use for AWJ cutting is the intensive wear of the focusing tube [24].

4. Conclusions

For all the tested abrasives, intense grinding of abrasive grains was observed during the jet formation in the cutting head. In this unfavorable phenomenon of disintegration, the abrasive grains, it has been observed that the disintegrated abrasive grains reveal new, sharp corners and cutting edges, which is beneficial because can be increase the efficiency of the cutting process.

It was also observed that the effect of abrasive concentration in the stream in the entire tested range from 15 to 22.5% has no significant effect on the degree and nature of the grinding of abrasive grains.

For garnet abrasives disintegrated at all concentration values the appeared the 20-25% predominance on of the grains below 53 µm. For all other abrasives disintegrated with each value of concentration values predominance of the grains about the size below 53 µm is bigger and equal 30%.

Based on the research, following detailed conclusions were drawn:

- The biggest recycling potential, from 51-61% range characterized garnet.
- For olivine, the recycling potential is equal 46%.
- Recycling potential of corundum is almost 40%, but abrasive wear of focusing tube is much bigger than garnet.

The additional benefit is the possibility of again application of used abrasive materials as a full-fledged product. It can solve the accumulation of used abrasives in landfills, generated by waterjet cutting on a massive scale.

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