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Environmental Aspects of Abrasive Water Jet Cutting

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1. Introduction

Among the methods of machining special attention they deserve environmentally friendly. This is mainly plastic processing (Kukielka 2003), (Kukielka & Kukielka 2006) and high pressure water jet technology. Use of conventional coolants in traditional machining and grinding is being looked upon critically from the point of view of its impact on environment.

In water jet machining is used pure (deionized) water with the addition of a small amount of abrasive (17-20% by mass).

Cutting by high-pressure water jet is one of advanced methods of materials machining. Treating materials using a high pressure abrasive water jet is more complex than conventional treatments. In addition, this advanced manufacturing technology replaces many operations traditionally carried out by cutting and does not cause structural changes in the machining material. Therefore, optimization of the machining is the subject of many studies (Hloch et al. 2007), (Perec 2016), (Valicek 2016). High pressure water is converted to a high speed jet inside a nozzle (Fig. 1a.) and flows out of the nozzle at a speed of several hundred meters per second, seizes abrasive particles and accelerates them to large kinetic energies.

Adding to the water jet the dry abrasive in a special mixer injector (Fig. 1b), causes increase cutting efficiency. As a result, it becomes possible to almost any material cutting with low roughness of cutting surface

(Perec et al. 2015). The most commonly used pressure in the system, called AWJ, ranges from 400 to 600 MPa and common abrasive is garnet (Perec 2011).

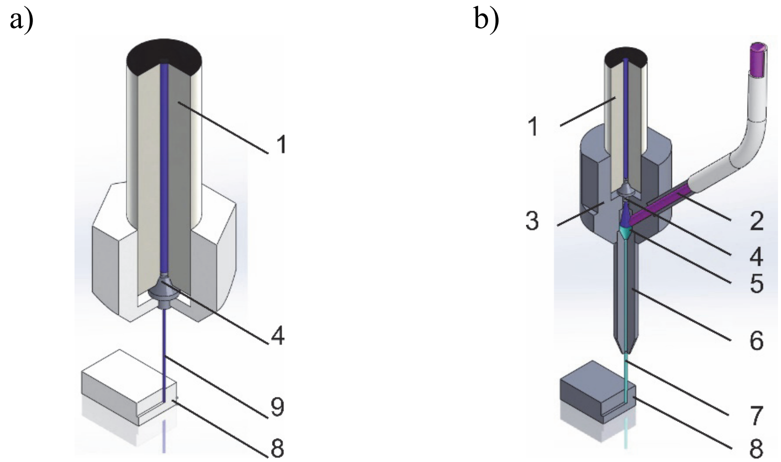


Fig. 1. Schematic diagram of Water Jet cutting (a) and Abrasive Water Jet cutting (b): 1. High pressure water inlet, 2. Abrasive inlet, 3. Cutting head body, 4. Water nozzle, 5. Mixing chamber, 6. Focussing tube, 7. High Pressure Abrasive Water Jet, 8. Machining sample, 9. High Pressure Water Jet
Rys. 1. Schemat cięcia strugą wody (a) oraz cięcia struga wodno-ścierną (b): 1. Dopływ wysokiego ciśnienia, 2. Dopływ ścierniwa, 3. Korpus głowicy tnącej, 4. Dysza wodna, 5. Komora mieszania, 6. Dysza wodno-ścierna, 7. Wysokociśnieniowa struga wodno-ścierna, 8. Przedmiot obrabiany, 9. Wysokociśnieniowa struga wody

Its popularity in the processing jet as an abrasive garnet is caused by achieving high performance at relatively low wear focusing tube (Hreha et al. 2014). The cost of abrasive is the main cost of processing an abrasive water jet (Perec & Tavodova 2016), therefore purposeful work aimed towards the use of the cheapest abrasive materials and their recycling. The roughness of the cut surface is comparable with the surface of the rough grinding and reaches a value R_a equal 2 μm (Perec et al. 2016).

2. Research materials

2.1. Abrasive materials

Garnet

The study used GMA Garnet abrasives supplied by GMA Garnet Pty Ltd, Western Australia. Almandine is the iron aluminium garnet. Almandine, like other garnets, forms rounded crystals with 12 rhombic or 24 trapezoidal faces or combinations of these and some other forms. This crystal habit is classic for the garnet minerals. Almandine is the most common of the garnets but seldom occurs in specimens worthy of collections or fit for gems. Almandine is usually found either as rocks forming mineral in magmatic and metamorphic acid rocks (such as migmatites, garnet-biotite gneisses, granulites, micaschists, pegmatites, diorites, etc.) or as heavy mineral sand from weathered hard rocks, secondary concentrated in present-day and/or pre-existing streams and other alluvial deposits or in present-day and/or pre-existing beaches and other shore line marine deposits. Only selected few localities are mentioned. Industrial abrasive made from garnet almandine is prevalent abrasive used in AWJ cutting.

Degree of damage of big crystals of garnet almandine (porphyroblasts) in rocks (i.e. number of individual particles limited by cracks in one porphyroblast (crystal)) plays an important role in determination of suitability of the almandine for production of industrial abrasive concentrate for AWJ cutting (Martinec et al. 2002). The properties of abrasives and view of crystal shape are shown in Table 1.

Table 1. Garnet (almandine) properties (Martinec et al. 2002)
Tabela 1. Właściwości granatu (almandynu) (Martinec et al. 2002)

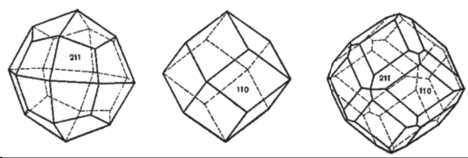
	
Crystal system	Cubic
Twinning	None
Unit cell	a = 11.53 Å

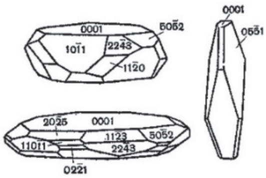
Table 1. cont.
Tabela 1. cd.

Habit	Crystals usually dodecahedrons or trapezohedrons; also in combination or with hexocathedron; massive; granular
Cleavage	1; {110} parting sometimes distinct
Fracture	Conchoidal to uneven
Tenacity	Brittle
Color	Deep red to reddish-brown, sometimes with a violet or brown or brownish black hue
Hardness (Mohs)	6.5-7.5
Density	4.1-4.3

Ilmenite

The study used ilmenite abrasives supplied by GMA Garnet Pty Ltd, under New Steel trade name. Ilmenite is an economically important and interesting mineral for production of titanium white pigment and titanium. It is named for its place of discovery at Ilmen Lake in the Ilmen Mountains, Ilmenite forms as a primary mineral in mafic igneous rocks and is concentrated into layers by a process called "magmatic segregation". It crystallizes out of a magma relatively early before most of the other minerals. As a result, the heavier crystals of ilmenite fall to the bottom of the magma chamber and collect in layers. It is these layers that constitute a rich ore body for titanium miners. Ilmenite also occurs in heavy sedimentary rocks (black fraction of sands). This mineral is very breakable and fragile (Martinec et al. 2002). The properties of abrasive and view of crystal shape are shown in Table 2.

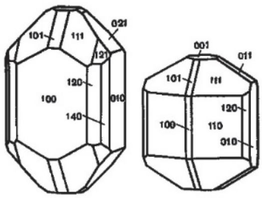
Table 2. Ilmenite properties (Martinec et al. 2002)
Tabela 2. Właściwości ilmenitu (Martinec et al. 2002)

	
Crystal system	Hexagonal
Twinning	On {0001}, simple; on {10-11}, lamellar
Unit cell	a = 5.09 Å; c = 14.09 Å
Habit	Crystals thick tabular or acute rhombohedral; granular; massive, lamellar to compact
Cleavage	2; {0001} and {10-11} parting
Fracture	Conchoidal to uneven
Tenacity	Brittle
Color	Iron-black
Hardness (Mohs)	5-6
Density	4.5-5.0

Olivine

The study used olivine abrasives supplied by Sibelco Europe under *Green Lightning Olivine* trade name. Fayalite is one of two minerals that are simply known as olivine. It is found in ultramafic igneous rocks. Mafic is a word that is used to define igneous rocks with a high iron and magnesium content. The olivine minerals have a high melting point and are the first minerals to crystallize from a mafic magma. Forsterite crystallizes first with fayalite crystallizing last when other minerals such as the pyroxenes are just beginning to form. The early crystallization of olivine is the reason that molten lavas can contain already crystallized grains of olivine before they are ejected from volcanoes. Some ultramafic rocks can be composed of almost all olivine and these are called dunites or peridotites. Olivine is also present in marbles that formed from metamorphosed impure limestones (Martinec et al. 2002). The properties of abrasives and view of crystal shape are shown in Table 3.

Table 3. Olivine (Fayalite) properties (Martinec et al. 2002)
Tabela 3. Właściwości oliwinu (fajalit) (Martinec et al. 2002)

	
Crystal system	Orthorhombic
Twinning	On {100}; on {031} as trillings
Unit cell	a = 4.799 Å; b = 10.39 Å; c = 6.063 Å
Habit	Crystals thick tabular, often with wedge-shaped terminations, small; massive, compact or granular
Cleavage	2; {010} and {100} imperfect
Fracture	Conchoidal
Tenacity	Brittle
Color	Greenish yellow, yellowish brown, brown
Hardness (Mohs)	7
Density	4.32

2.2. Focusing tubes

In research was used focusing tubes made from unique, patented materials that are literally changing the definition of wear resistance ROCTEC®100. The ROCTEC ®process enables the combination of these advanced ceramic materials without the need for a soft metal binder, as is the case with tungsten carbide/cobalt using traditional sintering technology. The ROCTEC process enables focusing tubes to be formed using very short consolidation cycles to minimize the natural tendency of ceramic particles to grow in size, when exposed to high heat for long periods. Eliminating a metallic binder and maintaining extra-fine grain size both contribute to optimum focusing tube performance. The result is an extremely durable material that fiercely resists abrasive and erosive wear.

3. Apparatus

The equipment used was a KMT Intensifier type I50, 2 axis CNC table type ILS55 by Techni Waterjet with computer control system (Fig. 3a). To capture abrasives after its exit from the focusing tube, a special receiver was used (Fig. 3b). The receiver was designed to collect the abrasives and to prevent any further particle disintegration after leaving the focusing tube. The bottom PVC receiver was covered by a steel plate to prevent perforation. No signs of wear were observed on the protective plate after conclusion of testing (Perec 2012). For establishing the particle size distribution of the abrasive, Retsch sieving equipment was used. The mass of abrasive remaining on the sieves was weighed on the digital lab scales. The statistical analysis of the abrasive materials grains distribution of was carried out using the Gradistat v.8.0 program (Blott & Pye 2001) based on the Folk & Ward method (Folk & Ward 1957). Microscopic photos of abrasive particles were taken on a microscope Olympus SZ-40.

a) b)

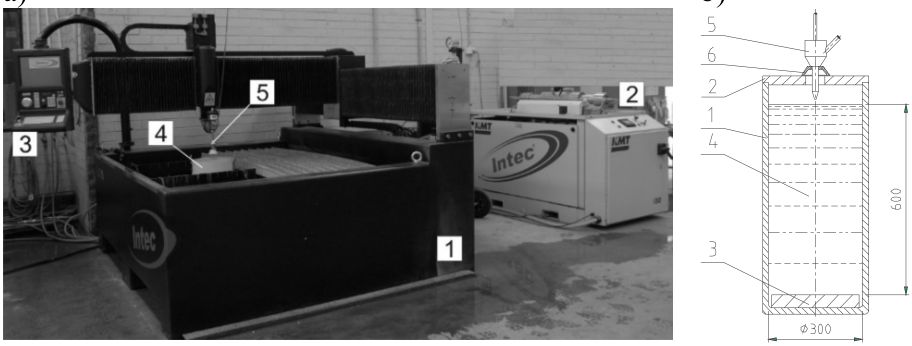


Fig. 2. Testing rig (a): 1) Cutting table, 2) Intensifier, 3) Control Unit, 4) Catcher, 5) Cutting Head, and catcher for abrasive jet (b): 1) Tank, 2) Tank Cap, 3) Mild Steel Shield, 4) Water, 5) Cutting Head, 6) Rubber Head Cap.
Rys. 2. Stanowisko badawcze (a): – 1) Stół roboczy, 2) Multiplikator ciśnienia, 3) Zespół sterujący, 4) Odbieralnik ścierniwa, 5) Głowica tnąca, oraz odbieralnik ścierniwa (b): 1) Zbiornik, 2) Pokrywa, 3) Osłona stalowa, 4) Woda, 5) Głowica tnąca, 6) Gumowa osłona głowicy.

3. Tests results

4.1. Abrasive grain disintegration

Garnet

The results of the study of GMA80 abrasive fractured during jet formation at a pressure of 390 MPa through a 0.25 mm orifice, 0.76 mm ID focusing tube and average of abrasive flow rate are shown in Fig. 3. The density function approximating the distribution before of the nozzle is symmetrical (Table 4) because skewness is near zero. Distribution is mesokurtic ($0.9<K_G<1.11$).

Table 4. GMA garnet particle distribution statistics
Tabela 4. Statystyczne parametry rozkładu ziaren granatu GMA

	GMA before	GMA after	GMA recycled
Skewness, Sk_G	0.039	0.248	-0.081
Kurtosis, K_G	0.920	0.651	0.908

Figure 4 shows sample abrasive grains before and after leaving the focusing tube. One can observe different size grains, mostly isometric in shape, but with sharp edges. Most grains are fine. Among them, you can see a few grains with larger dimensions.

After passing of garnet through the nozzle, density function of distribution change to asymmetric (fine skewed), with negative asymmetry and a predominance of the grains below 53 μm, which previously was not presented. Skewness equal -0.248. The volume of grains 425-250 μm decreased significantly. Distribution is very platykurtic, because kurtosis $K_G<0.67$.

In the process of recycling grains smaller than the limit (for garnet # 80 it is 125 μm) they are removed as inefficient during the cutting process [Perec, 2018]. The very small positive asymmetry density function approximating the grain distribution is also visible. Skewness is equal 0.081. Distribution is mesokurtic ($0.9<K_G<1.11$).

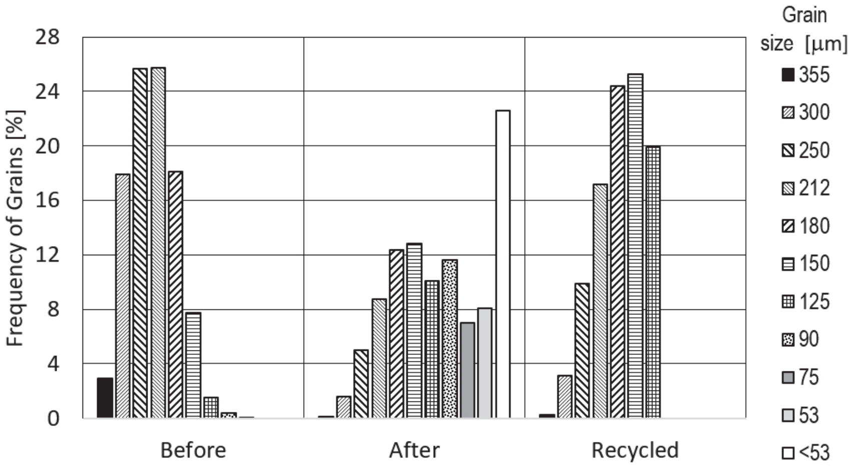


Fig. 3. Disintegration of garnet #80 after passing through cutting head with water nozzle ID 0. 2 mm and focusing tube ID 0.76 mm. Pressure 390 MPa
Rys. 3. Rozdrobnienie granatu nr 80 po przejściu przez głowicę tnącą z dyszą wodną Ø 0.25 mm i dyszą wodno-ścierną Ø 0.76 mm. Ciśnienie 390 MPa

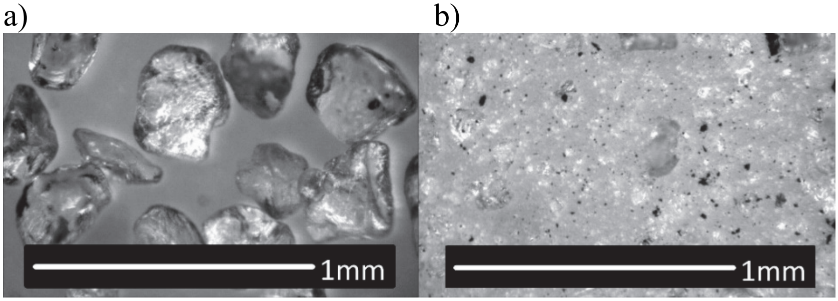


Fig. 4. Abrasive grains garnet 80 Mesh before (a) and after (b) forming in cutting head. Magnification 60 x
Rys. 4. Ziarna granatu nr 80 przed (a) i po (b) opuszczeniu głowicy tnącej. Powiększenie 60 x

Ilmenite

The study results of the Ilmenite abrasive fractured during formation of jets at a pressure of 390 MPa through a 0.25 mm dia orifice and 0.76 mm ID focusing tube are shown in Fig. 5. The density function approximating the distribution (Table 5) is coarse skewed ($0.1<Sk_G<0.3$). Distribution is leptokurtic ($1.11<K_G<1.50$).

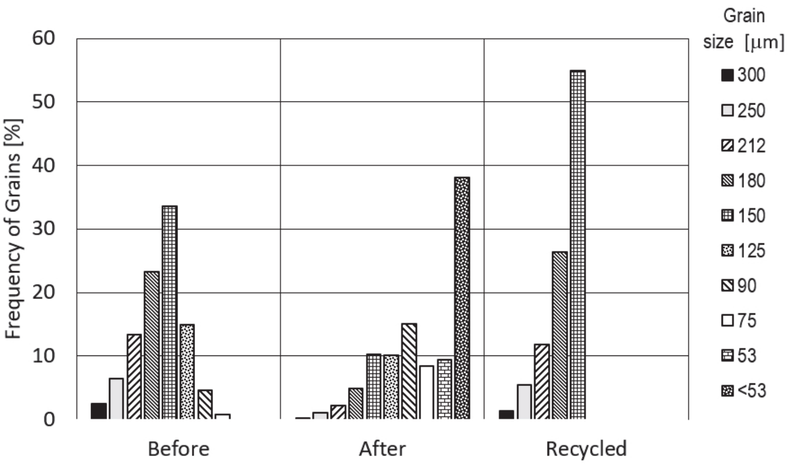


Fig. 5. Disintegration of Ilmenite #90 after passing through cutting head with water nozzle ID 0.25 mm and focusing tube ID 0.76 mm, Pressure 390 MPa.
Rys. 5. Rozdrobnienie ilmenitu nr 90 po przejściu przez głowicę tnącą z dyszą wodną Ø 0.25 mm i dyszą wodno-ścierną Ø 0.76 mm. Ciśnienie 390 MPa.

After passing of the ilmenite through the nozzle density function of distribution leave strong asymmetric (coarse skewed), with negative asymmetry and the predominance of the share of grains below 53 µm, which previously was not presented. Skewness equal 0.142. The share of grains 250-125 µm decreased significantly and volume of grains 90 µm increased. Distribution is very platykurtic (kurtosis $K_G<0.67$).

In the process of recycling grains smaller than the limit (for ilmenite #90 it is 90 µm) they are removed. The very coarse skewed density function approximating the grain distribution is also visible. Skewness is equal 0.39. Distribution is mesokurtic ($0.9<K_G<1.11$).

Table 5. Ilmenite particle distribution statistics
Tabela 5. Statystyczne parametry rozkładu ziaren ilmenitu

	Ilmenite before	Ilmenite after	Ilmenite recycled
Skewness, Sk_G	0.107	0.142	0.390
Kurtosis, K_G	1.134	0.632	1.017

Figure 6 shows sample abrasive particles of ilmenite before and after leaving the focusing tube. One can observe a very large number of very small grains and only few larger grains of ilmenite. This is confirmed by the distribution of abrasive particles as shown in Fig. 5.

a) b)

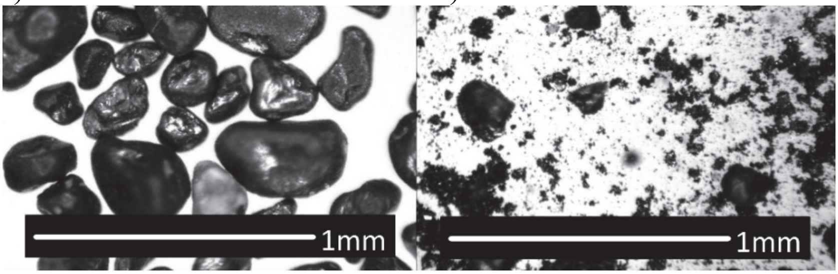


Fig. 6. Abrasive grains Ilmenite #90 before (a) and after (b) forming in cutting head. Magnification 60 x.
Rys. 6. Ziarna ilmenitu nr 90 przed (a) i po opuszczeniu (b) głowicy tnącej. Powiększenie 60 x.

Olivine

The study results of the olivine abrasive, disintegrated during jet formation at a pressure of 390 MPa through a 0.25 mm orifice, 0.76 mm ID focusing tube and average of abrasive flow rate are shown in Fig. 7. The density function approximating the distribution (Table 6) before the nozzle is fine skewed (skewness equal -0.139). Distribution is mesokurtic ($0.9<K_G<1.11$).

After passing through the nozzle persist fine skewed (skewness equal -0.139), with negative asymmetry and a predominance of the share of grains below 53 μm, which previously was not presented. Skewness equal 0.142. The volume of grains 300-180 μm decreased significantly. Distribution is very platykurtic (kurtosis $K_G<0.67$).

Table 6. Olivine particle distribution statistics
Tabela 6. Statystyczne parametry rozkładu ziaren oliwinu

	Olivine before	Olivine after	Olivine recycled
Skewness, Sk_G	-0.139	-0.134	0.197
Kurtosis, K_G	1.009	0.615	0.926

In the process of recycling grains, smaller than the limit (for olivine #60 it is 125 μm) they are removed as inefficient during the cutting process. The asymmetry (coarse skewed) density function approximating the recycled grain distribution is also visible. Skewness is equal 0.197 and distribution is mesokurtic ($0.9<K_G<1.11$).

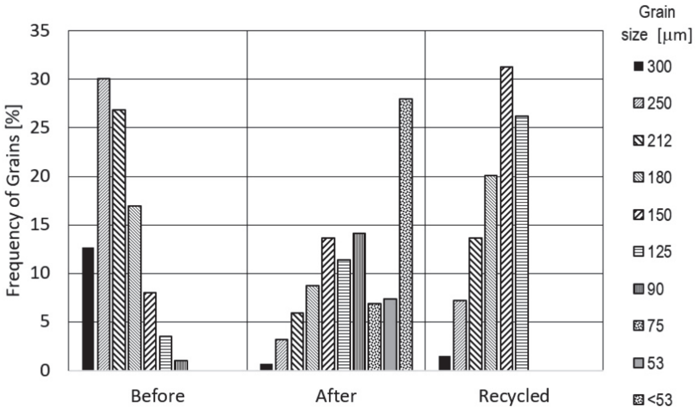


Fig. 7. Disintegration of olivine #60 after passing through cutting head with water nozzle ID 0.25 mm and focusing tube ID 0.76 mm, Pressure 390 MPa.
Rys. 7. Rozdrobnienie oliwinu nr 60 po przejściu przez głowicę tnącą z dyszą wodną Ø 0.25 mm i dyszą wodno-ścierną Ø 0.76 mm. Ciśnienie 390 MPa

Figure 8 shows abrasive particles before and after leaving the focusing tube. One can observe a large number of small grains and bigger grains of olivine. Lot of grains are fine.

a) b)

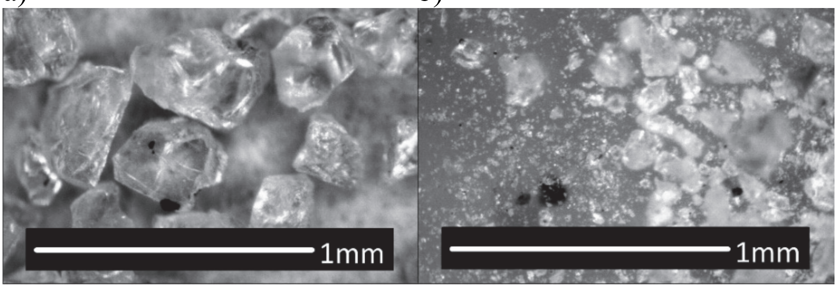


Fig. 8. Abrasive grains olivine #60: before (a) and after (b) forming in cutting head. Magnification 60 x
Rys. 8. Ziarna ilmenitu nr 60 przed (a) i po (b) opuszczeniu głowicy tnącej. Powiększenie 60 x

4.1. Recycling potential

After abrasive catching and drying sieve analysis was carried out and the analysis the amount of the individual fractions was determined. For test abrasive size #80 size range is from 300 to 125 μm. To determine what fraction of the original range found in the mass of particulate after treatment, all of the fractions smaller than the lower limit of the particle distribution, were rejected [Guo 1992]. It is illustrated in Fig. 3, 5, and 7.

The recycling rate was calculated on basis equation:

$$R_f = \frac{m_r}{m_t} \tag{2}$$

where:
R_r – abrasive recycling factor [g/g],
m_r – mass of recycled abrasive [g],
m_t – total mass of abrasive [g].

Specific results for tested abrasives are presented in Fig. 9. The biggest recycling factor, amounting to 0.51 was observed for the garnet. This means it can be expected that half of the spent abrasive is possible to re-use. The other abrasives was olivine, with the recycling factor equal to 0.32. This means that one third of the abrasive can be used again. The lowest potential recycling equal to 0.19, characterized ilmenite. In this only when not less than 1/5 could be used second time.

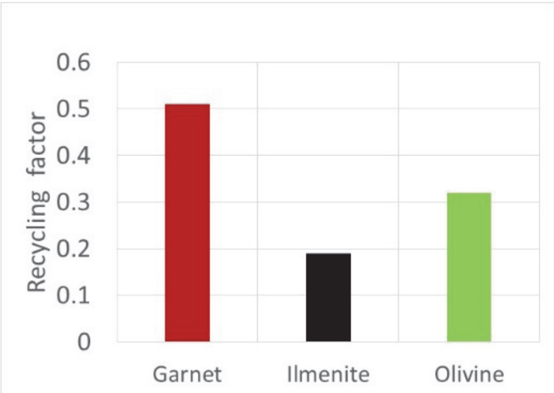


Fig. 9. Recycling rate for tested abrasives
Rys. 9. Wydajność recyklingu dla badanych ścierniw

4.3. Focusing tube wear

Erosive properties have an effect not only on the parameters of cut material but also on the durability of focusing tube (Barlić et al. 2008). On the studies basis, it's have identified the ability of erosion abrasive wear rates by calculating the focusing tube.

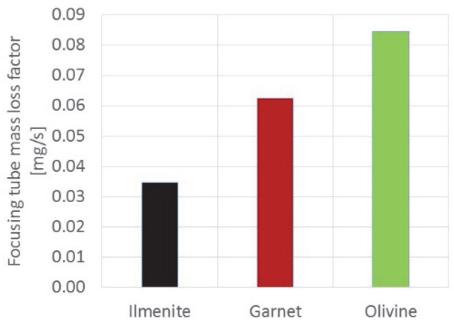
On Fig. 10 presented relation of focusing tube mass loss and abrasive flow for tested abrasive materials. The biggest focusing tube weight loss was observed for olivine. After the maximum test time, equal 7.2 min., the weight loss amounted to over 35 mg. The second in intensity order of focusing tube wear caused garnet type. After 7.2 min. loss in weight amounted 25 mg. Definitely the lowest focusing tube weight loss was observed for the ilmenite abrasive. After 7.2 min, wear was only 15 mg.

Focusing tube mass loss factor M_f is calculated based on the equation:

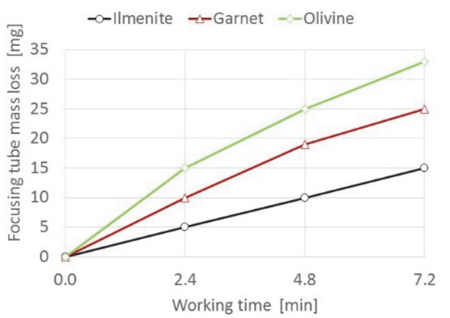
$$M_f(t) = \frac{\Delta m_t}{\Delta t} \tag{2}$$

where:
Δm_t – mass loss of focusing tube [g],
Δt – working time [s].

Illustrations of this equation for the tested abrasives shows Fig. 11.



Rys. 10. Współczynnik ubytku masy dyszy wodno-ściernej M_f dla badanych ścierniw
Fig. 10. Focusing tube mass loss factor M_f for tested abrasive



Rys. 11. Zależność ubytku masy dyszy wodno-ściernej od czasu pracy dla badanych ścierniw
Fig. 11. Relation of focusing tube mass loss and working time for tested abrasives

The highest focusing tube mass loss factor, equal to 0.084 is characterized by Olivine abrasive. For the garnet abrasive M_f factor is smaller and reaches value of 0.061. The smallest value of focusing tube mass loss factor, equal 0.035 gives ilmenite abrasive.

4. Conclusions

Based on the research following conclusions were drawn:

- the biggest recycling potential, over 50% characterized garnet,
- recycling potential of olivine is on 33% level, but abrasive wear of focusing tube is 20% bigger,
- recycling of ilmenite is not effective, despite the lowest focusing tube abrasive wear,
- further studies should test the cutting ability of recovered abrasive.

The possibility of again application of used abrasive materials as a full value in the process of water jet cutting on an industrial scale would largely resolve the problem of managing waste abrasives dumps. The recycling of abrasives makes the abrasive water jet machining greener, more sustainable, and more economical.

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Ekologiczne aspekty przecinania materiałów wysokociśnieniową strugą wodno-ścierną

Streszczenie

Tradycyjne metody produkcji mają negatywny wpływ na środowisko poprzez emisję produktów ubocznych procesu cięcia i erozji (wióry i mikrowióry), zużytej cieczy chłodząco-smarnej (oleje i emulsje, wzbogacone agresywnymi związkami chemicznymi) oraz wysokie zużycie energii. Nowoczesne systemy do obróbki mechanicznej powinny minimalizować ten wpływ. W artykule przedstawiono analizę zaawansowanej technologii produkcji – cięcia wysokociśnieniową strugą wodno-ścierną w aspekcie ochrony środowiska. W przeciwieństwie do tradycyjnej obróbki skrawaniem (szlifowanie, frezowanie) cięciu strumieniem wody nie towarzyszy emisja do środowiska pyłu i cząsteczek materiałów, które są szkodliwe. W artykule przedstawiono także analizę rozdrobnienia granatu – ścierniwa najczęściej stosowanego w tej technologii oraz ilmenitu i oliwinu oraz określono ich potencjał recyklingu.

Abstract

Traditional method of production has a negative impact on the environment by cutting and erosion products (chips and microchips), the used coolant (oils and emulsions, enriched aggressive chemicals) and high energy consumption. Modern systems for mechanical processing should be minimal this impact. This paper presented a study of advanced machining – Abrasive Water Jet (AWJ) technology in environmental aspects. Unlike traditional machining (grinding, milling) water jet cutting does not emit into the environment any dust or particles that are harmful if inhaled. Also presents an analysis of the fragmentation garnet – commonly used abrasive in this technology, ilmenite and olivine, and identified recycling potential of these abrasives.

Słowa kluczowe:
materiały ścierne, wysokociśnieniowa struga wody, aspekty ekologiczne, recycling, rozdrabnianie

Keywords:
abrasive, water jet, environmental aspects, recycling, disintegration