ABRASIVES AND POSSIBILITIES OF INCREASE IN EFFICIENCY OF ABRASIVE WATERJETS

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The contribution focuses on the research into abrasive materials and possibilities of adjustment of their properties in order to increase the efficiency of the processes of cutting and machining with abrasive waterjets. Cutting ability of commonly available garnet concentrates and non-traditional products which are starting to access to the Czech market were tested and compared. In addition, entirely new garnet products which are not commercially available yet, recycled abrasives, abrasives with various sizes of grains and heat-affected abrasives or abrasives coated with a thin plastic layer were studied.

KEYWORDS
high-speed waterjets, abrasive waterjets, abrasives, garnet, zirconia

1. INTRODUCTION

In processes of cutting or, in general, machining of materials by means of the technology of high-speed abrasive waterjet (AWJ), it is vital to use appropriate abrasive material which is accelerated by the waterjet and conducted to the area of interaction with a material to be cut. Abrasive materials are integral part of the abovementioned technology and they significantly influence the efficiency of the whole process. Various abrasive concentrates with required sizes of grains are commercially available at various price levels. Unfortunately, experience has shown that products of individual producers can differ considerably and it is often impossible to achieve the desired cutting effects. It is caused by differing composition of the products, genesis of mineral concentrates, insufficient separation of fine fraction, possible occurrence of imperfections in individual grains, etc. Another problem is the instable cutting ability of some mineral concentrates in the longer term, which reflects the changes in properties of original minerals in the course of quarrying.

The objective of this research was not only to compare most commercially available garnet abrasives used in the abrasive waterjet technology [Foldyna 1992b], [Foldyna 2000], [Foldyna 2001], [Martinec 2002b], but also to test other rather unusual concentrates, recycled abrasive, etc. Based on the knowledge and detailed studies of properties of abrasive materials (e.g. [Vasek 1991], [Vasek 1993], [Martinec 1994], [Martinec 1997], [Martinec 2002a], etc.), we have tried to adjust some of these properties to obtain better cutting results.

2. ABRASIVE WATERJETS

The scope of water jet applications has been significantly expanded by the addition of small grains of an abrasive material into the pure water jet. The abrasive water jets are able to cut the hardest known materials ensuring the high quality of the cut. The commonly-used abrasive water jet has a diameter of about 1mm and the resulting temperature in the area of the cut does not exceed 70 °C. Due to these properties, the AWJ technology represents a unique machining tool. Although the conception of the abrasive water jet is relatively old (the first abrasive mixing heads were already designed in 1935 and 1937 [Smith, 1936], [Tirrell 1939]), the real abrasive water jet [Hashish 1987] appeared for the first time in 1979. Since then, the AWJs have been applied in many sectors of industry and all versions of AWJ are largely used for cutting, especially.

Disintegration and comminution of mineral grains by high-velocity water jets are well known since the appearance of the abrasive water jet and the use of mineral grains as an abrasive material in the process of material cutting. Destruction of abrasive grains during their interaction with the water jet, mixing chamber walls and in focusing tube represents a negative phenomenon in the high-velocity abrasive water jet technology [Hlavac 1997], see Fig. 1. Substantial part of the destruction of abrasive grains is caused by the interaction of abrasive grains with the water jet and walls of the chamber. Additional destruction of grains occurs during their interaction with walls of a focusing tube and with material to be cut [Martinec 2002a]. Disintegration mechanisms which act in the process of disintegration of individual grains are described in details, for example, in [Sitek 2012]. It was found that the destruction of abrasive grains can be significantly influenced by the modification of a mixing chamber design [Foldyna 1992a], [Hlavac 2010].

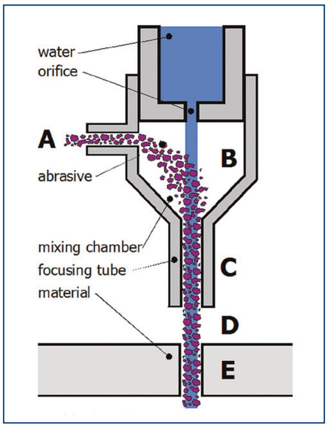

Figure 1. Abrasive particles in the process of high-velocity abrasive water jet cutting (A – input to mixing chamber, B – jet and abrasive mixing, C – focusing of the mixture, D – focusing tube output, E – material cutting)

3. METHODOLOGY FOR TESTING OF ABRASIVES

Cutting ability has been established the basic parameter of suitability of abrasives for the use in cutting process of materials by means of the AWJ technology. The cutting ability of abrasive material is one of the key factors for selection of a suitable abrasive material for specified AWJ applications. Therefore, a methodology for testing of cutting abilities of abrasive materials has been elaborated at the Institute of Geonics of the CAS [Martinec 1997]. The methodology is continuously innovated and made more precise according to new scientific knowledge using the latest available measurement and analytical equipment. Testing procedure is based on realization of non-through cuts under standard conditions in samples made from AISI 304 stainless steel. However, the methodology is also suitable for applications on other technical materials. In our research, other three testing materials were used, i.e. EN AW 6063 aluminum alloy, corundum ceramic material with content of 92 % Al_2O_3 and Silesian granite from the Erlich quarry in the location of Zulova (Jeseniky Mountains, Czech Republic). The methodology consists of the specification of testing and abrasive materials, procedure for realization of reference tests, and evaluation and interpretation of results. Test results are processed individually for each sample of an abrasive material in form of a test protocol. The protocol outlines the specification of the used abrasive material and results of the test in which the cutting ability of the tested abrasive is compared with the cutting ability of the reference abrasive (unit volume of material removed). The reference abrasive is the Barton's HPX 80 garnet for its long-term constant properties and perfect cutting ability. Results of tests can also be presented as graphs.

Apart from the cutting ability, other parameters and properties which help to better understand the behavior of a particular abrasive have been investigated. These are physical and mechanical properties, chemical composition, behavior after thermal treatment, etc.

4. TESTED ABRASIVES

Based on previous research, tests and analyses, several groups of abrasives were selected for laboratory and field tests:

- standard product of the Barton's 80 HPX garnet – this abrasive was used as standard abrasive for tests of cutting ability of the AWJ technology on individual materials,
- commonly used garnet products from worldwide producers (Australian garnet, Indian garnet),
- non-conventional products which are starting to access to the Czech market (Ukrainian garnet, zirconia),
- completely new garnet products which have not entered the Czech market yet (Tanzanian garnet, Mongolian garnet)
- recycled abrasives (recycled Australian garnet, recyclates from the Company PTV, Ltd.),
- abrasives of grain size of 120 MESH (Czech garnet, Australian garnet, Mongolian and Tanzanian garnet),
- heat-affected abrasives – the most commonly used abrasive product (Australian garnet) was heat-loaded at various temperatures,
- abrasive material with plastic coating – the most commonly used abrasive product (Australian garnet) was coated with various types of materials.

Sufficient quantity of abrasive concentrates (approx. 5 kg with grain sizes of 80 and 120 MESH) was prepared in order to carry out standard laboratory tests.

4.1 Thermal treatment of garnet concentrate

Due to the constant quality, the Australian garnet concentrate which is commonly used in the AWJ technology was selected for testing. Abrasive samples of about 5 kg were prepared by firing in a furnace at several temperatures and various periods of thermal loading. The samples were used to test the cutting ability of a particular abrasive material. Changes in cutting ability of the abrasive concentrate after various thermal loads were evaluated.

4.2 Coating of garnet concentrate grains by thin plastic layer

According to the specific method based on dipping the abrasives in a bath with particular vanish solution and subsequent air-drying and final sieving, sufficient quantity of the Australian abrasive concentrate with grains coated by a thin layer of different types of plastics was prepared for standard test of cutting ability. It was originally expected that the plastic layer on the surface of an abrasive grain would protect the grain from breakage in a mixing chamber or in a focusing tube (what often happens). And thus the relatively intact grain can participate in the cutting process. Another advantage of the plastic coating is the "filling" of possible cracks and discontinuities in abrasive grains. Four different plastic coatings were analyzed (Fig. 2): (i) one-part epoxy varnish, (ii) two-part epoxy varnish, (iii), nitrocellulose varnish and (iv) polyurethane-modified acrylic varnish. Fig. 2A shows the original abrasive material without coating for better comparison. However, the process for preparing coated abrasives is technologically complicated and time-consuming. It is supposed that other types of coating processes (metal, ceramics) should be discussed with experts.

5. TESTING ASSEMBLY

Equipment of the Department of Material Disintegration was used for the assessment of cutting ability of abrasives. Testing assembly consisted of the following parts:

- PTV 75–60 high pressure pump

(max. operating pressure of 415 MPa, max. flow rate of 7.8 $l \cdot min^{-1}$),

- X-Y cutting table PTV WJ2020-1Z-D (operating area of 2 000 x 2 000 mm, cutting speed continuously adjustable in the range of 0–20 $m \cdot min^{-1}$).

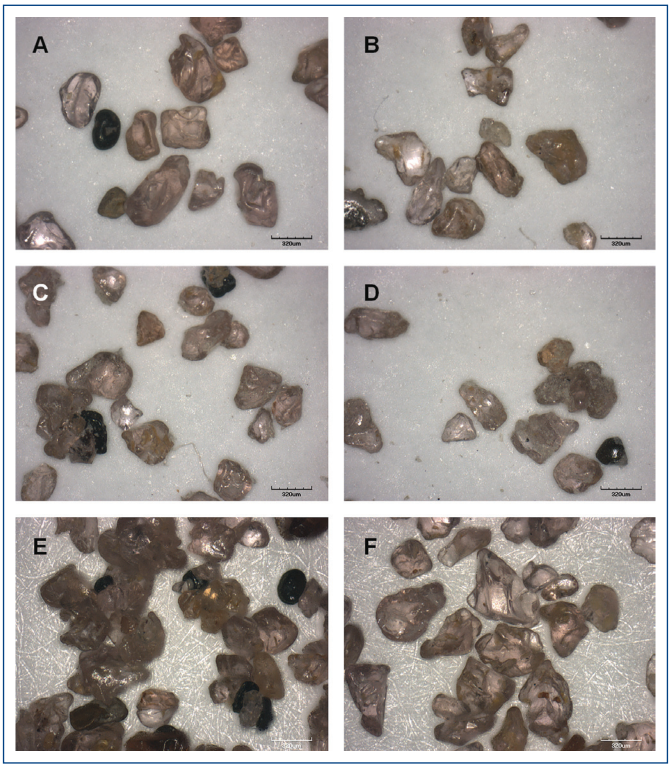

Figure 2. Australian garnet concentrates coated by thin plastic layer (A – original concentrate without coating, B – concentrate with one-part epoxy varnish coating, C – concentrate with two-part epoxy varnish coating, D – concentrate with nitrocellulose varnish coating, E – concentrate with polyurethane-modified acrylic varnish coating, F – same coating as in E, diluted 1:2). Change in appearance of individual grains coated by varnishes is distinct in comparison with original sample (A). Assemblies of grains glued together by varnishes can be also seen (compare E and F)

The below-mentioned measurement apparatus and analyzers were used for a detailed analysis of garnet concentrates before the realization of cutting ability tests:

- FRITSCH laser particle sizer Analysette 22 NanoTec (measurement range of 0.01–2000 μm),
- Olympus LEXT OLS 3100 confocal laser scanning microscope (resolution of 0.01 μm, total magnification of 120x~14400x),
- infra-red Thermo Nicolet Avatar 320 FTIR spectrometer (spectral range of 4 000–400 cm^{-1}),
- physical and mechanical properties were analyzed using the standard measurement and assessment equipment appropriate for a specific parameter,
- garnet concentrates were tempered in the laboratory muffle furnace PP40/45 of the Company LAC Ltd.

6. RESULTS OF TESTS OF CUTTING ABILITY OF ABRASIVES

All tested abrasives were compared with the Barton's 80 HPX garnet. The results are presented in form of graphs which are organized in order of types of abrasives listed in the chapter "Tested abrasives".

6.1 Commonly available garnet products

Commonly available commercial products from worldwide producers – the Australian garnet concentrate GMA 80 MESH and two concentrates from India with the grain size of 80 MESH, were tested. The products were compared to the Barton's 80 HPX garnet. The results are presented in Fig. 3. It is obvious that the Barton's garnet is the most suitable abrasive material to cut stainless steel. However, when homogenous medium-grained granite is cut, the cutting ability of the Indian garnet exceeds the cutting ability of the standard Barton's garnet of about 13 %. During granite cutting using the other garnet products, the increase in cutting efficiency is not so significant. But they still cut better than the Barton's garnet. Unfortunately, the graph also reveals that the Indian products are of unstable quality (both concentrates came from the same supplier) and thus demonstrate unstable cutting efficiency.

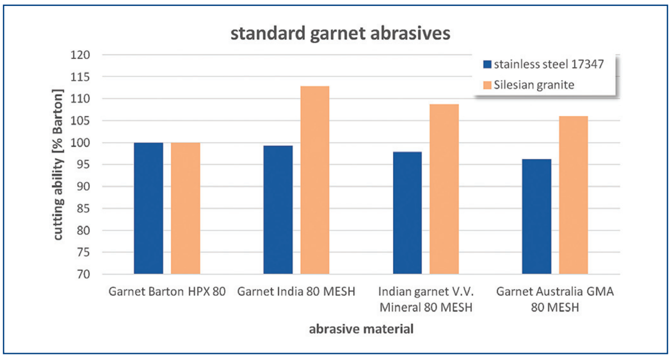

Figure 3. Cutting ability of some commonly available garnet concentrates

6.2 Non-conventional abrasives

Especially a new product on the Czech market – the Ukrainian garnet concentrate UGM 80, has been included in this group. This concentrate has not yet been studied sufficiently in the AWJ technology. Another abrasive material is the cubic zirconia with some pieces of diamonds. Both abrasives were compared to the Barton's 80 HPX garnet (Fig. 4 and Fig. 5). The Ukrainian garnet was tested on stainless steel and granite; the cubic zirconia on aluminum alloy and ceramic material.

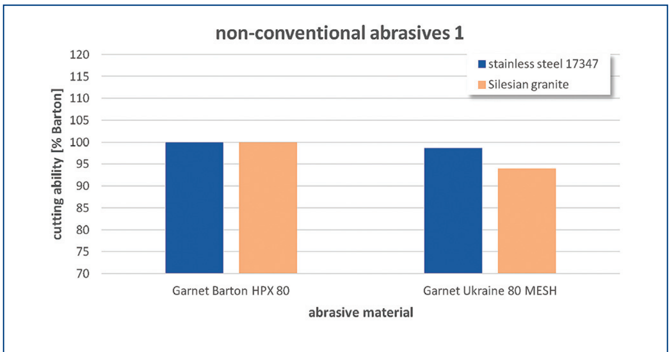

Figure 4. Cutting ability of Ukrainian garnet

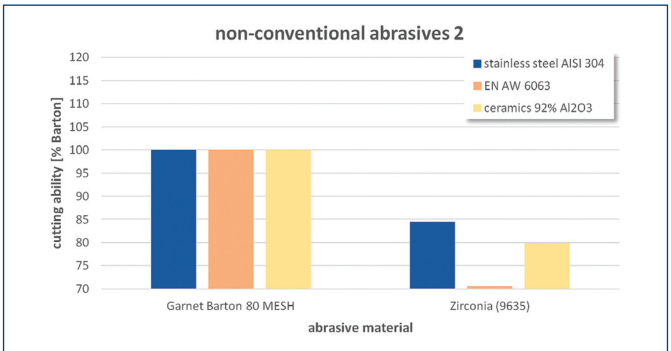

Figure 5. Cutting ability of cubic zirconia

6.3 New garnet products

New prospective garnet products from Mongolia and Tanzania which have not yet entered the Czech market related to the AWJ technology were studied exclusively (Fig. 6). They are waste materials produced during the mining of garnets used in jewelry. Specially for these test, a small amount of garnet concentrates of the grain size of 80 mesh from the localities in Mongolia and Tanzania were prepared (it is not the garnet product commonly available on the market under the name Mongolian Garnet, Rock Garnet or Alluvial Garnet mined in the central part of the Inner Mongolia, which is currently the locality in China). Two Tanzanian products and one Mongolian product were tested with excellent results in cutting stainless steel and ceramics. In this case, all products exceeded the cutting ability of the Barton's garnet (in stainless steel equally of about 4 %, in ceramics up to 20 %).

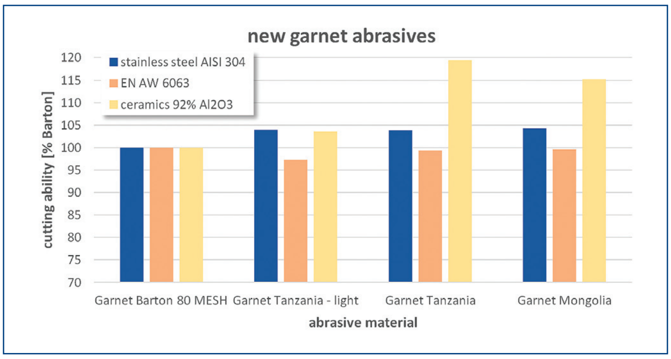

Figure 6. Cutting ability of new garnet abrasives

6.4 Recycled abrasives

Recycled abrasives can significantly contribute to the reduction of costs of the whole process of abrasive waterjet cutting. Four garnet recyclates prepared from the already used Australian garnet were tested. Grain size distribution curves of individual abrasive concentrates used are presented (Fig. 7) in order to provide further insight into the problem. Cutting performance of some of the recyclates exceeded expectations (Fig. 8), as deterioration in cutting ability was expected. Traditionally, the recyclates performed worst in aluminum alloy. Cutting ability of some concentrates increased up to 3% in stainless steel and up to 5 % in ceramics.

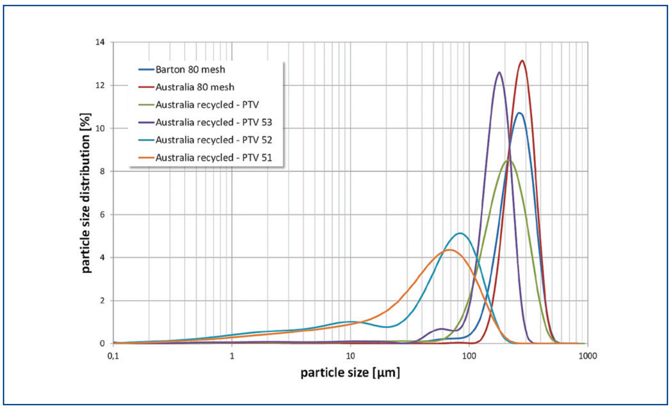

Figure 7. Particle size distribution of recycled abrasives used

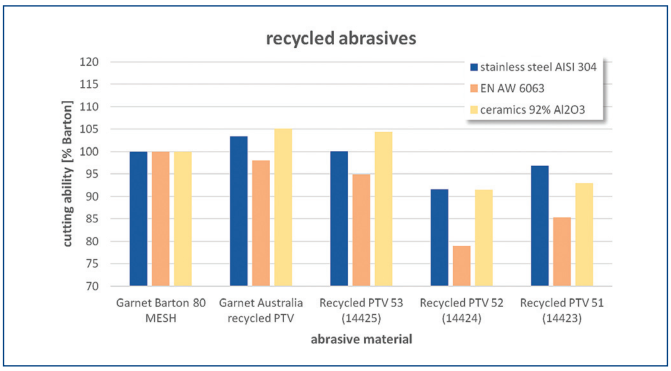

Figure 8. Cutting ability of recycled abrasives

6.5 Abrasives of smaller size of grains (120 MESH)

Abrasive material of 80 MESH (size of grains about 0.2 mm) is usually used in standard abrasive water jet cutting processes. However, for finer cutting and in order to achieve better quality of a cutting surface or in micro-cutting applications, finer abrasive material of 120 MESH (size of grains about 0.125 mm) is used. Four garnet concentrates with the size of grains of 120 MESH were tested. The results were first compared to the Barton's 80 HPX garnet, as a finer product from the Barton supplier was not available. However, it was required to compare products of the same size of grains (in this case, Australian garnet GMA 120 MESH – Fig. 9). The worst results were achieved with the Czech garnet GBK. Cutting performance of finer fractions of the Mongolian and Tanzanian garnets was rather the same. Their results were, however, worse than results of the Australian garnet.

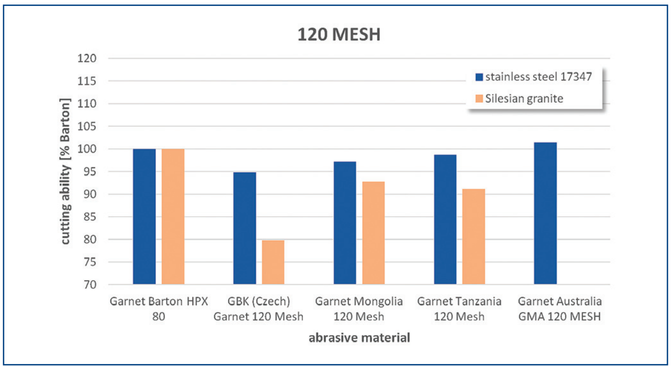

Figure 9. Cutting ability of fine abrasives

6.6 Thermally treated abrasives

It was presumed that thermal treatment of garnet abrasive material would cause the elimination of imperfections or tensions in individual abrasive grains and the grains would not thus break so easily during the process of mixing with the waterjet in the mixing chamber or during the process of the waterjet focusing in the focusing tube. This should increase the cutting efficiency of the cutting process and improve the transfer of the kinetic energy of the abrasive waterjet in the interaction with the cut material.

The Australian garnet concentrate was thermally treated. The samples were heated up to the desired temperatures (500, 600, 700, 800 and 900 °C) for 20 minutes or 4 hours. Results are shown in Fig. 10 and Fig. 11. Certain improvement in cutting ability in comparison to the original Australian garnet concentrate can be first observed on samples heated at 900 °C for 4 hours. However, slight improvement in cutting ability (about 3% during stainless steel cutting) is offset by the energy intensity during the preparation (thermal treatment) of abrasives.

6.7 Abrasives coated by thin layer

Grains of the Australian garnet were selected to be coated by a thin plastic layer due to their availability and long-term stable properties.

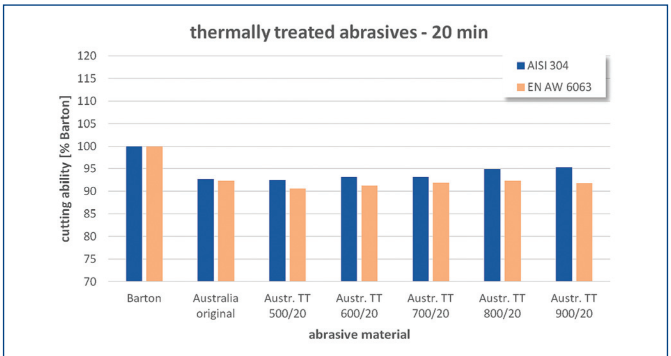

Figure 10. Cutting ability of abrasives thermally treated at various temperatures for 20 minutes

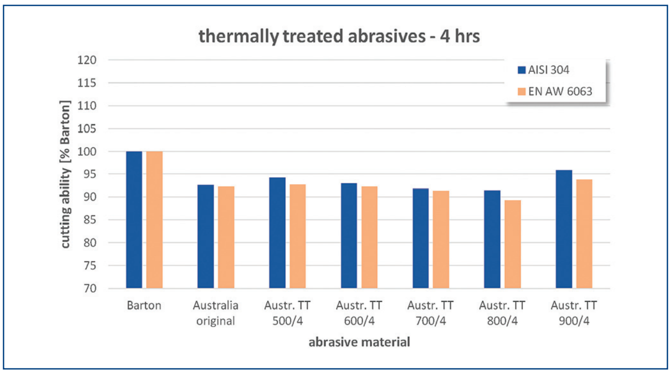

Figure 11. Cutting ability of abrasives thermally treated at various temperatures for 4 hours

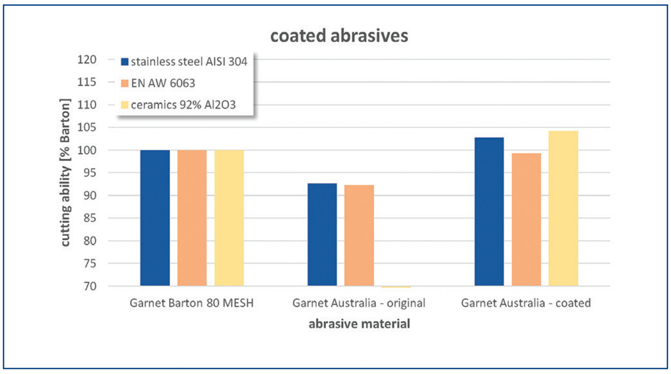

Figure 12. Cutting ability of abrasives coated by a thin layer of the polyurethane-modified acrylic varnish

Different types of coating layers at various concentrations were tested (see the chapter "Coating of garnet concentrate grains by thin plastic layer"). Some problems with dosage of abrasives occurred as the increased surface friction of the coated grains caused the blocking of the supply of abrasives into the cutting head. The smallest difficulties regarding the preparation and dosage of abrasives were experienced using the abrasive material coated by a thin layer of the polyurethane-modified acrylic varnish. This type of coating was therefore used in cutting ability tests.

Obtained results (Fig. 12) demonstrate improved cutting ability during cutting of stainless steel (about 3% better than the Barton's garnet) and ceramics (about 4 % better than the Barton's garnet). In comparison to the original type of abrasive material, the cutting ability was improved of about 11 % in stainless steel cutting and more than 7 % in aluminum cutting. Similar results were achieved using the recycled Australian garnet concentrate PTV (Fig. 8). It is supposed that it is caused by a similar mechanism of fracturing of grains: the recycled abrasive material no longer contains inclusions and cracks in grains as it was already used in the process of cutting. It thus eliminates fracturing of grains during the process of waterjet mixing and focusing. Similarly, the applied coating covers the abrasive grain and penetrates into cracks. The grain is "glued together" and further fracturing is avoided.

7. CONCLUSION

Based on the long-term research, various types of abrasive materials were prepared in a way to increase their cutting ability during the process of machining and cutting using the high-speed abrasive waterjet technology. In some cases, significant increase in cutting ability up to tens of percent in comparison to the standard best commercially available Barton's 80 HPX (e.g. cutting of ceramics using the Tanzanian garnet) was achieved. However, some expectations were not met (e.g. use of zirconia or thermal treatment of abrasives). It was found that it is advantageous to use one specific abrasive material for a specific material to be cut. An abrasive material efficient for cutting one material often cuts another material less efficiently. Appropriate selection can thus significantly increase the cutting ability of an abrasive material.

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