HARDNESS AND ELASTICITY OF ABRASIVE PARTICLES MEASURED BY INSTRUMENTED INDENTATION

PAVOL HVIZDOS[1], MICHAL ZELENAK[2], SERGEJ HLOCH[2]
[1]Structural Ceramics Department
Institute of Materials Research of the SAS
Kosice, Slovakia
[2]Department of Material Disintegration
Institute of Geonics of the CAS, v.v.i.
Ostrava, Czech Republic

DOI:10.17973/MMSJ.2016_03_201601

e-mail: phvizdos@saske.sk

Basic mechanical properties of seven types (from seven different sites) of abrasive garnet particles used for water jet cutting were measured using the technique of instrumented indentation (also called depth sensing indentation or nanoindentation). Hardness and modulus of elasticity were evaluated and compared. All the abrasives had similar measured mechanical properties (hardness 20 – 24.16 GPa), the highest values were found for the Czech garnet.

KEYWORDS
abrasive, garnet, hardness, elasticity, instrumented indentation

1. INTRODUCTION

Water jet cutting typically uses a mixture of water and abrasive to more effectively cut through materials. A pure waterjet (one without abrasives) is effectively only for very soft materials, such as rubber or food products. Adding abrasive, however, greatly enhances the cutting capability and the abrasive waterjet can cut through steel [Hennies 2010].

The overwhelming choice for most waterjets is garnet abrasive. The most frequent type is red garnet. It is fairly hard and when it fractures, it forms sharp edges. Both of these qualities are advantages in waterjet machining. Garnet is also relatively chemically inert, and won't react with materials being cut, making its disposal simpler as well. For cutting softer materials, such as aluminium, often other, less hard and cheaper minerals can be used [Hennies 2003, Oh 2014].

Mined garnet is typically found mixed with other minerals and must be blasted out of the mine. Then it is crushed, and separated from the rest of the rock. The crushing causes the edges of the garnet to be sharp, and therefore cut better with less taper and minimal burr.

The usability of garnets from different suppliers and/or mining sites can differ due to their variability in their mechanical properties, namely hardness and stiffness. The aim of the present paper was to compare such mechanical properties of several different garnet abrasives.

2. EXPERIMENTAL MATERIALS

Samples of various garnet grains were delivered in the form of loose powders and were designated according to the origin as shown in Tab. 1 together with information about typical particle sizes.

Garnet site	Particle size	Size unit
Australia	0.180-0.250	mm
Barton Mines	0.180-0.250	mm
Czech	2-3	mm
India	0.180-0.250	mm
Mongolia	0.180-0.250	mm
Ukraine	0.180-0.250	mm
Tanzania	0.180-0.250	mm

Table 1. Designation of powder samples and typicle particle sizes

The samples were embedded in metallographic resin. They were ground and polished by a series of diamond grinding and polishing discs so that clear and smooth cross sections were obtained. The final surface roughness Ra was lower than 0.05 μm.

3. EXPERIMENTAL METHOD

Instrumented indentation represents a modern technique which, unlike the traditional hardness testing, does not rely on observation of the indent made by hard tip on the surface of the tested material. It rather continuously records the depth of penetration (*h*) into the material with respect to the actual applied load (P). The result is a loading, or *P-h*, curve as it is schematically shown in Fig. 1. From the known geometry of the tip and its material properties a number of data about the tested material can be inferred.

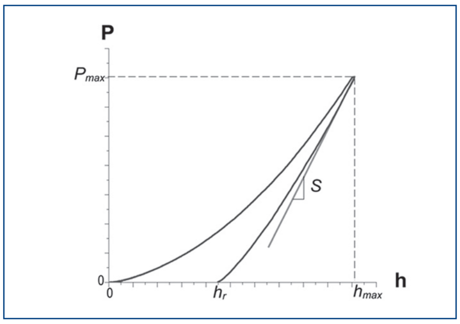

Figure 1. Typical load (*P*) vs. penetration depth (*h*) curve of a load-unload instrumented indentation test, where the designation of various quantities is illustrated: the maximum load (P_{max}), maximum penetration depth (h_{max}), residual depth (h_r), and contact stiffness (*S*). After [Fischer-Cripps 2002].

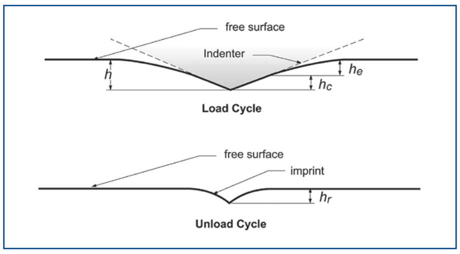

Figure 2. Scheme of the contact between indenter and material in the loading and the unloading cycle. Contact depth (h_c), elastic depth (h_e) and residual depth (h_r) are marked. After [Oliver and Pharr 1992].

Indentation hardness, H_{IT}, then can be calculated as the mean pressure over the contact area

$$H_{IT} = P_{max} / A(h_c) \quad (1)$$

where *A* (*h*) is the contact area as function of depth of penetration (*h*), which for Vickers (four sided pyramid) and Berkovich (three sided pyramid), Fig. 3, is the same:

$$A(h)=24.5\ h^2 \quad (2)$$

From the unloading part of the *P-h* curve the so-called contact stiffness *S* is calculated

$$S = dP/dh \mid h=h_{max} \quad (3)$$

Also, contact depth h_c is estimated as

$$h_c = h_{max} - \varepsilon\ P/S \quad (4)$$

where ε is a geometric factor, which for Berkovich indenter tip is 0.74. Based on these also elastic response of the system can be evaluated as

$$E^* = \sqrt{\pi}\,/2\ .\ S\ /\ \sqrt{A(h_c)} \tag{5}$$

where E^* is a composite modulus of elasticity whose value is

$$1/E^* = (1-\nu_i^2)/E_i + (1-\nu_s^2)/E_s \tag{6}$$

E and ν are the elasticity modulus and Poisson´s ratio, respectively. Subscripts i and s refer to indenter and sample, respectively.

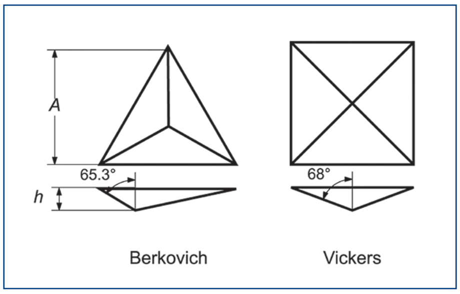

Figure 3. Angles and relationship between the area and indentation depth of the most employed sharp indenters in nanoindentation: Berkovich and Vickers.

Hardness and modulus of elasticity were measured by means of Nano Hardness Tester (Fig. 4) NHT-TTX by CSM Instruments, Switzerland, using Berkovich indenter tip. The indents were placed on the samples surfaces so that they were not influenced by occasionally present pores, far from the grain edges, and also far from each other so that they could not interact. The placing of the indents inside a typical abrasive particle

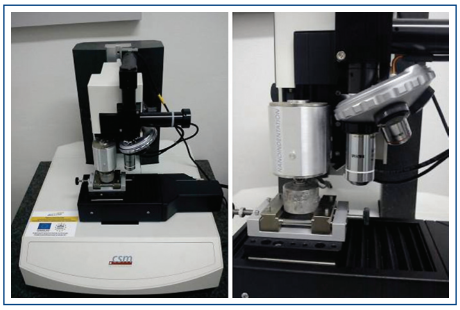

Figure 4. Nanoindenter NanoHardness Tester (NHT) by CSM Instruments. Overall view (left), detail of the programmable table with a sample and the measuring head (right).

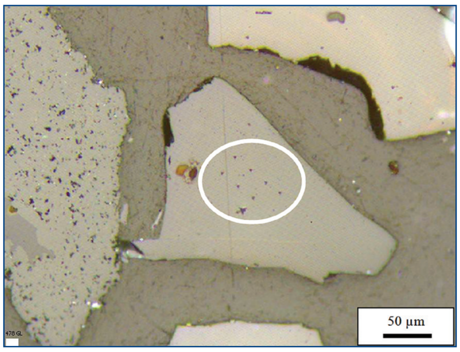

Figure 5. Location of the matrix of indents inside a typical abrasive particle, sample Tanzania.

is illustrated in Fig. 5. Thus, the stress fields developed during loading were safely inside undisturbed material volume. On each material at least six indents were made and the results were statistically treated.

Standard simple loading-unloading mode was used. Maximum load was 100 mN, loading rate was 200 mN/min, and the dwell time at the maximum load was 10 s.

From the obtained "load vs. depth of penetration" curves values of hardness and modulus of elasticity were calculated according to [Oliver and Pharr 1992].

4. RESULTS

The results of instrumented indentation are summarized in Tab. 2, where the average values and standard deviations of hardness (H_{IT}) and modulus of elasticity (E_{IT}) are shown. As it can be seen the scatters of measurements were small, which means that the samples were sufficiently homogeneous and the indents were placed in a correct way.

The experimental P-h curves averaged over all indents in each material are shown in Fig. 6. It is clear that the Czech garnet stands out as the hardest and stiffest material while the others pretty much overlap.

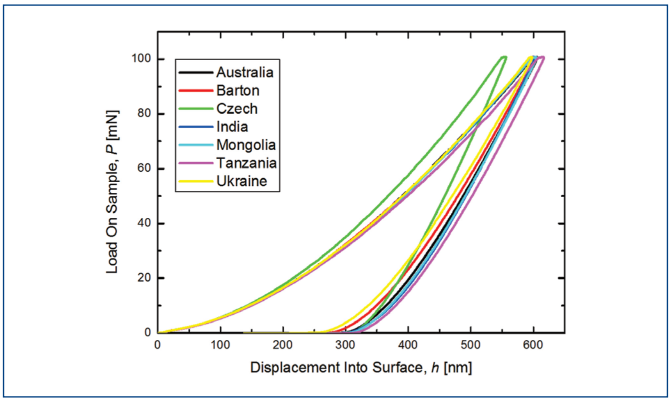

Figure 6. Averaged P-h curves for all experimental materials.

In Figs. 7a to 7g abrasive particles with indents in all samples are shown. It should be noted that in the Tanzania sample (and to a lesser extent also in the Australia one) the indents are accompanied by indentation cracks, emanating from the indent corners. Such behavior is not frequent at used tip geometry and loadings, and it suggests significant brittleness of the material. This, however, might not be a detrimental in itself, since brittleness means that the particles would break and create sharp edges easily, which actually might improve the final cutting properties.

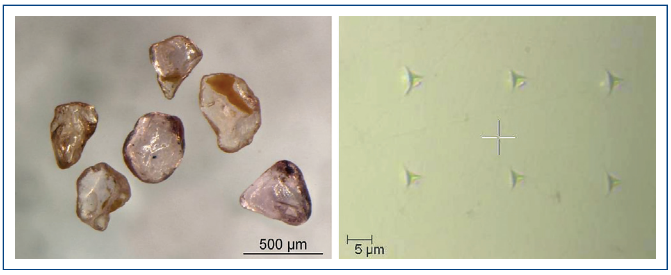

Figure 7a. Australia

		Australia	Barton	Czech	India	Mongolia	Tanzania	Ukraine
H_{IT}	Mean	21.68	22.56	24.16	20.81	21.26	20.33	23.64
[GPa]	Std Dev	0.38	1.72	0.08	0.25	0.39	0.41	1.09
E_{IT}	Mean	205	201	271	220	211	204	197
[GPa]	Std Dev	4	3	1	5	4	4	5

Table 2. Average values of hardness and modulus of elasticity od the experimental materials.

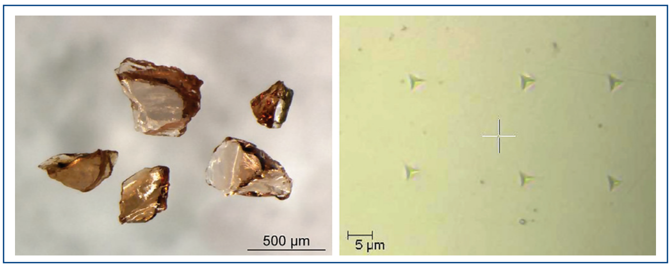

Figure 7b. Barton

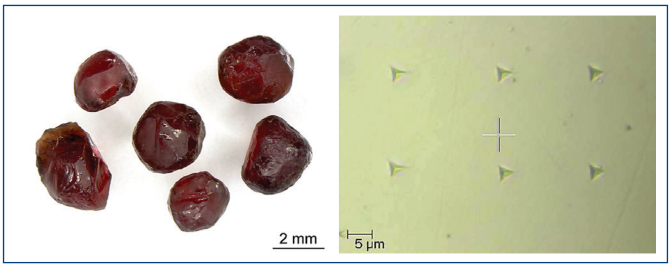

Figure 7c. Czech

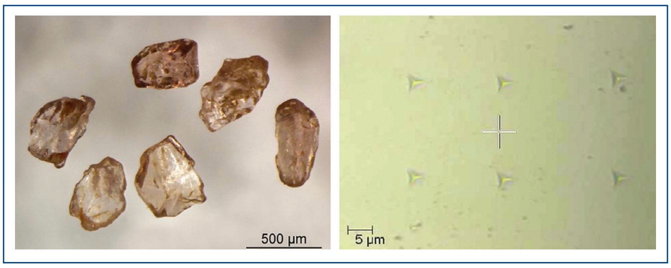

Figure 7d. India

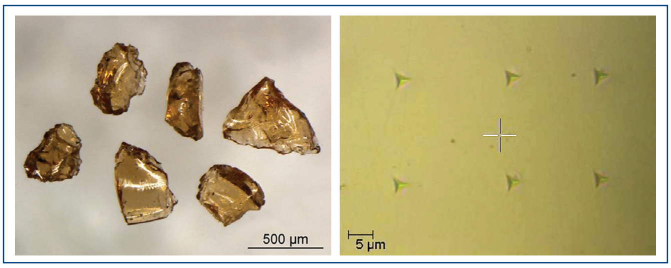

Figure 7e. Mongolia

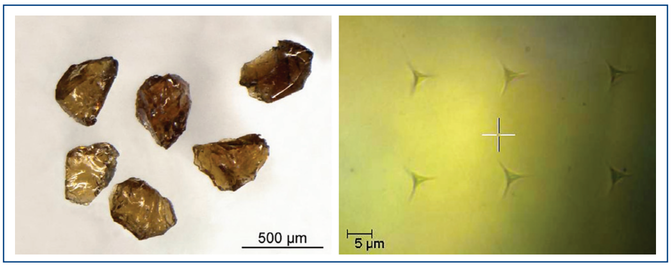

Figure 7f. Tanzania

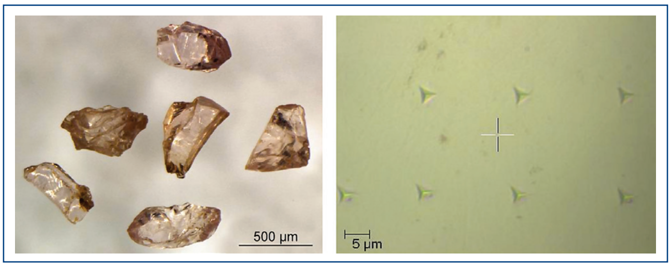

Figure 7g. Ukraine

5. CONCLUSION

Mechanical properties of seven garnet samples used as abrasives for water jet cutting were evaluated by instrumented indentation. Hardness of all materials were relatively similar regardless of particle sizes. The highest hardness and elasticity was found for the Czech garnet, the lowest for Tanzania and India, while Tanzania and Australia samples were the most brittle ones.

ACKNOWLEDGEMENTS

The work was supported by the project 15_PA07-C1 (WORTH) of the EU, and by projects VEGA 2/0075/13 and APVV-0108–12 of Slovak Republic.

REFERENCES

[Fischer-Cripps 2002] Fischer-Cripps, A. C. Nanoindentation. New York: Springer, 2002. ISBN 978–1-4899-0515-4.

[Hennies 2010] Hennies, W. T., et al. Applications of ultra high-pressure powder-abrasive waterjet, Materials Science Forum, 2010, vol. 660-661, 1137–1144, ISSN: 02555476.

[Hennies 2003] Hennies, W. T., et al. Technological characteristics of garnets for ultra-high pressure water jets, Materials Science Forum, 2003, vol. 416-418, issue 1, 41-46, ISSN: 02555476.

[Oh 2014] Oh, T. M., et al. Crush characteristics of abrasive particles during abrasive waterjet rock cutting, In Geomechanics from Micro to Macro – Proceedings of the TC105 ISSMGE International Symposium on Geomechanics from Micro to Macro, IS-Cambridge 2014, vol 2, 1577–1581, ISBN: 978–113802707-7.

[Oliver and Pharr 1992] Oliver, W. C. and Pharr, G. M. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. Journal of Materials Research, 1992, vol. 7, issue 6, 1564–1580, ISSN 0884-2914.

CONTACT

Pavol Hvizdos, PhD.
Institute of Materials Research
Slovak Academy of Sciences, Structural Ceramics Division
Watsonova 47, Kosice, 04001, Slovakia
tel: +421 557 922 402, e-mail: phvizdos@saske.sk