TURNING OF MATERIALS WITH HIGH-SPEED ABRASIVE WATER JET

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The paper describes and analyses own experiences concerning technology of turning by high-speed abrasive water jet. Technology development as well as present stay-of–the-art in given area are introduced in brief. Possibilities of application of such machining method especially in the area of hard and difficult-to-machine materials as well as rocks and wood are discussed.

KEYWORDS
abrasive water jet machining, turning, steel, rock, wood.

1 INTRODUCTION

In addition to already standard cutting of materials by a high-speed abrasive water jet (2D machining), the technology of turning by the high-speed abrasive water jet can be applied for the production of spatial rotation-symmetrical bodies. Turning by the water jet is similar to the conventional single-point turning by a mechanical tool on a lathe, since a workpiece rotates and a cutting tool is continually moved parallel to the workpiece axis and incrementally fed toward the axis of the workpiece. Contrary to the classical turning, the water jet can be moved in all directions with much larger lateral increments. Jet forces on the workpiece are negligible. The material removed from the workpiece is converted to very fine debris, as opposed to the chips formed by conventional turning [Hashish 1995]. All advantages of standard cutting by the abrasive water jet can also be applied to the turning with the jet: possibility to machine even difficult-to-machine materials, almost zero thermal effects on the cutting surface of the workpiece, possibility to carry out various operations with the same tool during one clamping of the workpiece, one technological manufacturing method used for various shapes of the workpiece and various materials, etc. (see Fig. 1).

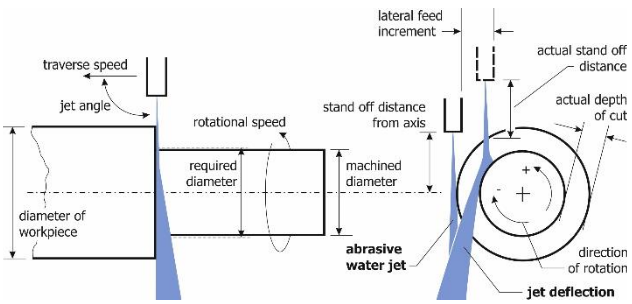

Figure 1. Scheme of turning by abrasive water jet

2 TECHNOLOGY DEVELOPMENT

The idea of turning materials with high-speed water jets is almost thirty years old. It was given in specific form through the development of the abrasive water jet technology. The first study covering the turning with the abrasive water jet was already published by [Hashish 1987]. [Ansari et al. 1992] carried out extensive research on the visualisation of the process of turning with water jet using a high-speed camera. In the same year, [Ansari 1992] created a simplified physical model of water jet turning while [Zeng et al. 1994] developed a mathematical model. [Henning 1999] published his empirical approach to this issue and [Hashish 2001] presented later on results of the research on effects of operating parameters during the water jet turning on the quality and appearance of surfaces in terms of macroscopy. [Zhong 2002] published their experience with turning of glass. [Hlavac 2006] turned a wide range of materials, i.e. from fragile non-homogeneous, ductile to plastic materials. [Manu 2008] investigated the effect of jet angle during the process of turning of aluminium alloys and they also published a model of turning of ductile materials on the basis of erosion of the studied material [Manu 2009]. Recently, process of turning by abrasive water jet was examined for instance by [Hloch et al. 2014] - turning of titanium, [Hlaváček et al. 2015] - turning of sandstone and [Hutyrova et al. 2015] - turning of wood plastic composites. The works published over the past decades are mostly focused on investigation of the effect of operating parameters (flow rate and grain size of abrasives, rotational speed and direction of rotation of the workpiece, traverse speed, jet angle, etc.) on the feed rate of the material, quality, size and shape accuracy of turned surfaces, respectively on the mechanism of material disintegration in place of the interaction of the jet and workpiece or creation of the most accurate model of the process of turning (for example [Li et al. 2013] and [Liu et al. 2014]). Although there is nothing to be criticised in experimental approach of these studies, there are only few practical applications where the existing method of turning can be clearly replaced by the new technology - for economic reasons especially (achieving significantly higher productivity, compliance with production tolerances, reduction of costs and reduction of production time, etc.). It appears that the turning with high-speed abrasive water jet will not become a universal and broadly applicable technology in the near future. However, despite higher costs, it can be used for some special applications where other methods of turning cannot be applied or can be only applied with difficulties. [Biskup et al. 2004] described an interesting application of the technology, for instance, in medicine. He and his colleagues turned interference screws made of bovine bones used for the reconstruction of the Anterior-Cruciate-Ligament of the knee joint. [Axinte et al. 2009] applied the abrasive water jet to profile and dress grinding wheels. He discovered that the grinding wheels were profiled not only cheaper, but also faster compared to the mechanical method of turning with diamond cutting tools used so far.

Own experience with turning of various metal and non-metal materials by the means of the abrasive water jet, including the knowledge and some generally applicable principles which we found out after the evaluation of experiments, are presented in other chapters to inform professional public about this progressive technology.

3 TURNING OF ROCK MATERIALS

We used the technology of turning with the abrasive water jet due to its specific character for the preparation of rock samples for determination of some physical and mechanical properties of rocks and geocomposites.

3.1 *Testing samples for strength tests*

Rock materials show significant bi-modularity, which means that values of compressive strength and tensile strength differ considerably. While tests of the uni-axial compressive strength on these materials cause no problems and values of the compressive strength form the basis for the classification of rocks, tests of the tensile strength are much more complicated. It is especially difficult to get the right shape of testing samples and to fix the samples in jaws of a lathe (see, for example, [Vutukuri et al. 1974]). Preparation of testing samples using mechanical methods is very difficult, in case of some rocks even impossible. Application of the abrasive water jet is one of methods which can solve this problem.

Earlier research showed that the method of processing of rock samples (by diamond saw and water jet) did not affect the resulting physical and mechanical properties of the testing samples [Konečný 1998]. It enabled preparation of testing rock samples of unconventional shapes which could not be achieved so far by means of other processing methods or the shape of the samples was too difficult or economically disadvantageous to be realised (for example, [Konečný et al. 2000]). Testing rock samples of "dog-bone" shape [Labuz 2007] were prepared due to the application of the abrasive water jet.

After successful realisation of tensile testing on these samples, rotationally symmetric rock samples (Figure 2) were made, the shape of which was inspired by the shape of test pieces for tensile testing of metals (for example, the standard ČSN 42 0314). In terms of the theory of mechanics, samples with round cross-section are more suitable for tensile testing that the "flat" samples. The shape with centrally reduced section eliminates problems which occur by cylindrical samples for tensile testing. The cylindrical samples are often damaged in the vicinity of the area where they are glued in the steel clamp bushing because of frequent multi-axial state of stress occurring in the area of sample gripping or changes of rock properties in the area of gluing in bushings (rock saturated or not saturated with the glue).

Results of tensile testing on samples prepared by the water jet were published in [Sitek et al. 2005]. The cylindrical core of homogenous Godula sandstone with a diameter of 36 mm which was drilled by the conventional method using a diamond core bit was stepwise turned and the testing samples were made.

Figure 2. Testing samples turned from sandstone

3.2 *Experimental equipment and procedure*

Equipment for sample manufacturing consisted of a source of the high pressure water (multiplicator pump of 415 MPa), a conventional PASER II cutting head and an X-Y cutting table for the movement of the jet over the samples. The workpiece was clamped in chucks powered by an electric engine with a frequency converter which permitted gradual change of workpiece rotations in the range of 0 to 1000 rpm.

The jet parameters were set up according to the recommendations which were presented by [Hashish 1995] on the basis of his research. He found that higher jet pressures generally produced smoother surfaces and higher removal rates of the workpiece material. The rotational speed was found to be insignificant in affecting turning results, at least between 400 and 2500 rpm. This implies that the accurate setting of rotational speed is not a critical when turning with abrasive water jets. As the quality of created surfaces is concerned, a reduced increment size with an increased number of increments and finer abrasive material produce a smoother surface without greater roughness and waviness. The jet parameters were thus set as follows: water nozzle diameter of 0.33 mm, water pressure at the nozzle exit of 350 MPa, focusing tube diameter of 0.8 mm and spindle speed (i.e. rotation of the samples) of 600 rpm. Garnet with the grain size between 0.15 and 0.18 mm, which corresponds to 90 MESH at the international scale of particle sizes, with the abrasive flow rate of 250 $g.min^{-1}$ was used.

The workpiece faces were made by the method of face turning with a moving jet [Hashish 2000]. Because of the round workpiece profile, the nozzle had to move in the vertical direction in order to maintain a constant stand-off distance of 2 mm. The cutting speed of the cutting head during face turning was 0.83 $mm.s^{-1}$.

Side shape of the workpiece is formed by a complex surface created by combination of diameter turning of cone turning methods. The required shape was achieved by two passes of the jet: the first pass was made to remove material from the workpiece; the traverse speed was 0.83 $mm.s^{-1}$. The second pass for finishing the final shape of the workpiece was made at different setting of jet parameters to eliminate rough surface, jet striation marks, worse roundness and inconsistent diameter. The traverse speed of the second pass was set to 0.42 $mm.s^{-1}$ with lateral feed increment of 2 mm. The stand-off distance between the focusing tube and the workpiece surface was 2 mm again.

Tensile strength testing was consequently carried out on the prepared samples. Tensile strength of rocks and tensile deformation modulus (also called the Young´s modulus of elasticity) were obtained. The results were compared with results of tensile strength tested on cylindrical samples and with indirect tensile strength testing methods (for example, the Brazilian test).

Several tens of samples from rocks (various types of sandstones, quartzite, marble and limestone) and geocomposites (composites created in the process of injection on the basis of rock - used as skeleton - and injection chemical binders – for instance [Soucek 2005] were made. Relatively homogenous fine-grained materials were intentionally selected, while the sample size has the crucial role in non-homogenous materials during testing of strength properties [Van Mier 2002]. It is appropriate to follow generally accepted recommendations that the length of the tested cylindrical part should be approximately five times bigger than the diameter of the tested part and that the diameter of the tested part should be minimally ten times bigger than the biggest diameter of grain in the material. The samples were prepared mostly from cylindrical semi-products. When the original shape was a prism, the so-called shape memory effect occurred and the shape of the sample reminded the original cross-section of the sample due to considerable jet flexibility even after significant reduction of the diameter.

Several rock samples of this type were also made for the Strata Mechanics Research Institute of the Polish Academy of Sciences. The mechanism of tensile damage of these samples was studied in detail there and the obtained results were compared with the Brazilian test [Nowakowski et al. 2009].

4 TURNING OF WOOD

Wood is a soft material which can be easily processed by conventional turning. This method is used especially for the production of rotating components of furniture, furniture accessories, toys, lighting units, etc. By conventional turning, the properties of wood (hardness, tendency to cracking, etc.) and its state (dry or wet, fresh or old, etc.) are considered in particular. Generally, wet and fresh wood is better to be machined. However, most of these properties are not crucial during the process of turning by the abrasive water jet. The only important parameter is the water absorption of a particular type of wood. By high saturation of the workpiece, the shape and dimensions of the workpiece can be changed during consequent drying of the wood, which can cause undesirable cracking.

Wooden semi-products with a diameter of 50 mm prepared from two types of wood, i.e. birch and oak, were turned in the laboratory. The effect of jet traverse speed on the quality of the turned surface at low rotational speed of the workpiece was studied. Parameters of the turning process were set as follows: diameter of the water nozzle of 0.33 mm, water pressure at the nozzle of 400 MPa, focusing tube diameter of 0.9 mm and workpiece rotational speed of 34 rpm. Australian garnet of 80 MESH with the abrasive flow rate of 400 g.min^{-1} was used as abrasive.

Turned surfaces are smooth and of good quality depending on the operating conditions and determined process parameters. Grooved (screw-like) surface, see Figure 3, is created at higher traverse speeds of the jet due to low rotational speed of the workpiece. The surface appearance and quality of both treated wood types differ rather by the inner structure and composition of a particular type of wood than by the impact of the jet. The surface turned by the water jet shows better quality and lower roughness in comparison to the surface turned by a conventional cutting tool. However, the technology of turning with the abrasive water jet cannot compete with the conventional turning method in terms of rapidity and cost-effectiveness.

Figure 3. Surfaces turned from wood

5 TURNING OF GRAPHITE

Although graphite is a soft material, it splits and breaks during chip machining due its inner structure. Dust level is also significantly increased. In addition, force effects of the cutting tool on the workpiece must be minimized during machining of particularly thin components to eliminate damage of the workpiece caused by cracking, chipping, etc.

An electrode for the technology of electrical discharge machining (EDM) was turned from a cylindrical graphite semi-product in the laboratory. Because of material properties, the electrode was first turned by pure water jet without addition of abrasives. However, the material was cracking and split. The next attempts were done with the abrasive water jet. Dust level during machining was significantly reduced. Surface of rather good quality was created after turning at high water pressure (400 MPa), with abrasive flow rate of 400 g.min^{-1} and at low rotational speed of 34 rpm, even with changing traverse speed of the jet over the workpiece (up to 10 mm.min^{-1}). Nevertheless, the required tolerance was not achieved, which is a general problem of water jet turning. The determined dimensions of the workpiece were, however, fulfilled in the interval of ± 0.2 mm.

The technology of turning with the abrasive water jet is suitable for rough processing of graphite. Final treatment to get specific dimensions and to fulfil the required tolerance must be done by other method. Economic aspect and effectiveness of the entire process should be considered for each case individually.

6 TURNING OF METALLIC MATERIALS

Chip machining of standard metallic materials does not cause any problems. This technology has been innovated and improved several times in the course of its development and it has become almost perfect due to automatization, computer control of the entire process and application of virtual reality and artificial intelligence. Chip machining, however, reaches increasingly its limits with the development of new technical materials. Unconventional technologies of machining thus start to play an important role. The abrasive water jet appears to be a promising technology for turning of hard and difficult-to-machine materials.

Figure 4. Turned surfaces of metals (from the left: Monel, titanium, Incoloy)

6.1 *Tested materials*

Some of difficult-to-machine materials were selected to be turned by abrasive water jet: Incoloy, titanium, Monel, Manaurit and Inconel.

Character of roughness of turned surfaces as well as shape and dimensions of the workpiece turned at various turning speeds (1.5 to 7.5 $mm.min^{-1}$) and at low rotational speed of the workpiece (34 rpm) were studied in particular. Significant increase in roughness at increasing traverse speed of the jet did not occur by the studied materials at process parameters set as mentioned above. The increasing traverse speed, however, caused increase in the workpiece diameter. It is understandable, since lower amount of abrasive particles came into contact with a particular area of the turned surface. The jet thus "has little time" for sufficient material removal. Relatively smooth surfaces (Figure 4) were achieved at low rotational and traverse speeds. As in case of graphite, the abrasive water jet technology can be used for roughing and preparation of difficult-to-machine metallic materials prior to final treatment of surfaces by other methods.

Effect of selected parameters and turning process was particularly studied on Inconel. Therefore, a special chapter is devoted to it. Knowledge arising from experiments performed at the Institute of Geonics is presented.

6.2 *Inconel*

Inconel represents a group of austenitic chromium-nickel steels, the so-called superalloys (i.e. alloys of excellent mechanical strength showing creep resistance at high thermal loading and resistance against corrosion and oxidation). Inconel is predetermined to be used at high temperatures and in extreme conditions due to its properties. It is extremely difficult to be machined by conventional methods because of rapid mechanical strengthening during turning. For this reason, abrasive water jets are applied for cutting of Inconel sheets.

Figure 5. Turning of Inconel bar

6.3 *Procedure and results*

Prisms of cross-section of about 40 x 40 mm were prepared for testing. Several turning parameters (workpiece rotational speed, direction of workpiece rotation, method of turning, various traverse speed, various lateral feed increment, number of passes, abrasive flow rate and total duration of the turning process) were tested on the samples prepared in this fashion in order to determine, if the jet may compete with conventional methods of turning. The same equipment was used as for turning of rock samples (Figure 5).

Twelve cylindrical surfaces in total with a final diameter of 36 mm (Figure 6) were turned from the prisms by various turning methods. Resulting appearance of turned surfaces and duration of turning were evaluated. The results can be summarised as follows:

- Square cross-section showed significant shape memory effect. It was necessary to cut off the edges prior to turning in order to accelerate the turning process (Figure 7a). Elimination of the memory effect was only possible by very slow turning at discontinuous (step-by-step) traverse speed or turning of an already cylindrical workpiece.
- Turning at discontinuous traverse speed has been proven advantageous. It means that the jet impacted on the workpiece in one position of the cutting head a sufficiently long period. More or less grooved surface was created (Figure 7b) depending on the size of the step.

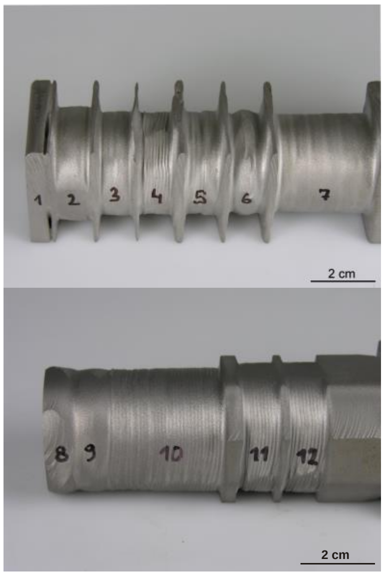

Figure 6. Cylindrical surfaces turned from Inconel

- Direction of workpiece rotation "toward the jet" accelerated material removal from the workpiece. However, resulting surface was rougher (Figure 7c).
- Smoother surface was created at lower rotational speed (60 rpm). Effect of higher rotational speeds (up to cca 600 rpm) on surface quality was negligible.
- Last pass should be done very slowly in order to create a smooth surface. Higher speed and especially the acceleration at the beginning of the traverse movement and deceleration at the end of the movement resulted in creation of a "barrel-like" cylindrical surface (Figure 7d).

- Higher abrasive flow rate significantly shortened the duration of turning (increase in abrasive flow rate from 230 g.min^{-1} to 750 g.min^{-1} resulted in reduction of duration of the turning process by almost ½).
- Inconel is a very hard material which must be turned a rather long time to get the required diameter (the minimum time to get a turned surface of 10 mm in length was about 6 minutes). It has been shown that the abrasive water jet technology could not compete with conventional methods of chip machining of Inconel, since the turning process took long time and, in particular, the resulting surface was of relatively bad quality (in comparison with chip machining). In addition, the precise shape and dimensions of the workpiece could not be followed.

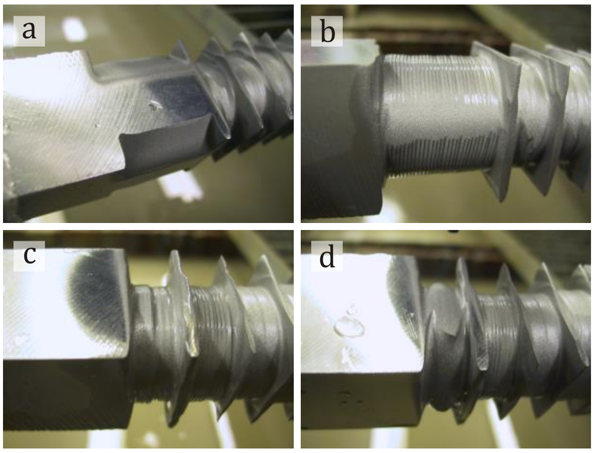

Figure 7. Creation of cylindrical surfaces (a – cut-off of edges prior to turning, b – grooved surface, c-left part – effect of direction of workpiece rotation, d-left part – "barrel-like" surface)

- However, turning with the abrasive water jet can be applied on difficult-to-machine materials as primary technology for pre-treatment and preparation of surfaces to be consequently finished by chip machining. If the semi-product is a bar of square cross-section (as in this case), cracking and damage of mechanical cutting tools occur during discontinuous cut during chip machining. This disadvantage is completely eliminated by turning with the abrasive water jet.

7 CONCLUSION

It is obvious from the research carried out at the Institute of Geonics of the CAS as well as from experiences gathered at other institutions that the turning with the abrasive water jet cannot currently replace the conventional chip machining with mechanical tools and, in particular, it is not suitable for mass production of components made from commonly-used metals. However, there are some applications where the jet is quite effective and provides with better performance than many standard methods of turning. It mostly concerns special applications where the conventional turning methods cannot be used or their use is economically unattractive. Rather than to compete with the existing machining methods, this technology complements other technologies due to its unique properties.

One of special applications useable in geomechanics, geotechnics, rock and construction industry where the conventional methods are not applicable is the laboratory production of test samples from geomaterials used for testing of physical and mechanical properties. The production of one sample took about ¼ to ½ hour depending on the material, including preparation works. It is possible to produce any kind of test sample (not only of cylindrical and square shapes) by the abrasive water jet technology. This initiates development of new methods of testing which could not be realised so far because of problems occurring during production of suitable test samples (samples of unconventional shapes, samples with various discontinuities, shape notches, etc.).

This technology can be used for preparation of surfaces which are consequently finished by other methods, for example by chip machining. The application of abrasive water jet can eliminate many deficiencies of conventional chip machining (thermal effects on the turned surface, force effects of the cutting tool on the workpiece, etc.). Assessment of possible application of the abrasive water jet in the process of turning and determination of its cost-effectiveness in comparison with other methods should be done for each specific case individually.

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REFERENCES

[Ansari 1992] Ansari, A., Hashish, M. On the Modeling of Abrasive-Waterjet Turning. In: LICHTAROWICZ, A. (ed.): Jet Cutting Technology, Proc. 11th intern. conf., St. Andrews, 8-10 September, 1992. Dordrecht: Kluwer Academic Publishers.

[Ansari et al. 1992] Ansari, A., Hashish, M. and Ohadi, M. Flow Visualization Study on Macro Mechanics of Abrasive-Waterjet Turning, Journal of Experimental Mechanics, December, 1992.

[Axinte 2009] Axinte, D. A. et al. Abrasive waterjet turning – An efficient method to profile and dress grinding wheels. Int. J. of Machine Tools & Manufacture 49, 2009, pp 351-356.

[Biskup 2004] Biskup, C., Louis, H., Pude, F., Kirsch, L. and Schmolke, S. Machining of bony interference screws by means of an abrasive waterjet, in Colin Gee (ed.): Water Jetting, Proc. 17th intern. conf., Mainz, 7-9 September, 2004. Bedfordshire: BHR Group.

[CSN 1980] CSN 42 0314 Test pieces of circular cross-section with heads for holding rings for tensile testing of metals (in Czech). Czechoslovak State Standard, Praha, Office for Standards and Metrology, 1980.

[Hashish 1987] Hashish, M. Turning with Abrasive-Waterjets - A First Investigation, ASME Transactions, Journal of Engineering for Industry, 1987, 109 (4), pp 281-296.

[Hashish 1995] Hashish, M. Abrasive Jets. In Labus, T.J. (ed): Fluid Jet Technology: Fundamentals and Applications, St. Louis, WJTA, 1995, pp 4.1-4.52.

[Hashish 2000] Hashish, M., Stewart, J. Observation on Precision Turning with Abrasive – Waterjets In Ciccu, R. (ed.):

Jetting Technology, Proc. 15th intern. conf., Ronneby, 6-8 September, 2000. Bedfordshire, BHR Group.

[Hashish 2001] Hashish, M. Macro characteristics of AWJ turned surfaces. American Waterjet Conference, Minneapolis, Minnesota, 2001, WJTA, pp 45-58.

[Henning 1999] Henning, A. Modeling of Turning Operation for Abrasive Waterjet, in Hashish (ed.): Proc. 10th American Waterjet Conference, Houston, 14-17 August, 1999. St. Louis, WJTA.

[Hlavac 2006] Hlavac, L. M. et al. Testing of parameters for turning by abrasive water jets. 18th Int. Conf. on Water Jetting, Gdansk, Poland, BHR Group, 2006, pp 123-128.

[Hlavacek 2015] Hlavacek, P., Carach, J., Hloch, S., Vasilko, K., Klichova, D., Klich, J. and Lehocka, D. Sandstone Turning by Abrasive Waterjet. Rock Mech Rock Eng, 2015, 48:2489–2493.

[Hloch 2014] Hloch, S., et al. Abrasive waterjet (AWJ) titanium tangential turning evaluation. Metalurgija = Metallurgy, 2014, Vol. 53, No. 4, pp 537-540.

[Hutyrova 2016] Hutyrova, Z., Scucka, J., Hloch, S., Hlavacek, P. and Zelenak, M. Turning of wood plastic composites by water jet and abrasive water jet. Int J Adv Manuf Technol, 2016.

[Konecny 1998] Konecny, P., Sitek, L. Two technologies of rock samples cutting: their effect on samples strength properties. In Rossmanith (ed.): Mechanics of Jointed and Faulted Rock MJFR-3, Proc. 3rd intern. conf., Vienna, 6-9 April, 1998. Rotterdam, Balkema.84:1615–1623.

[Konecny 2000] Konecny, P., Kozusnikova, A. and Scucka, J. New method of testing tensile strength of rocks. In Geotechnika i budownictwo specijalne, Proc. 23rd winter school of geomechanics, Bukowina Tatrzanska, 13-17 March, 2000. Krakow, AGH.

[Labuz 2007] Labuz, J.F. et al. Experiments with rock: Remarks on strength and stability issues. Int. J. of Rock Mechanics and Mining Sciences 44, 2007, pp 525-537.

[Li 2013] Li, W. et al. An investigation into the radial-mode abrasive waterjet turning process on high tensile steels. International Journal of Mechanical Sciences, December 2013, Vol. 77, pp 365-376.

[Liu 2014] Liu, D. et al. Modeling and optimization of operating parameters for abrasive waterjet turning alumina ceramics using response surface methodology combined with Box-Behnken design. Ceramics International 2014, Vol. 40, Issue 6, pp 7899-7908.

[Manu 2008] Manu, R. et al. Influence of jet impact angle on part geometry in abrasive waterjet turning of aluminium alloys. Int. J. of Machining and Machinability of Materials 3 (1-2), 2008, pp 120-132.

[Manu 2009] Manu, R. et al. An erosion-based model for abrasive waterjet turning of ductile materials. Wear 266, 2009, pp 1091-1097.

[Nowakowski 2009] Nowakowski, A. et al. Tensile strength of rock – comparison of results of direct tension test and Brazilian test (in Polish). Proceedings of scientific works of VŠB - Technical University of Ostrava 2009, Issue 2, Vol. IX, Civil engineering series, pp 201 – 217, ISBN 978-80-248-2119-1, ISSN 1213-1962.

[Sitek 2005] Sitek, L. et al. Shaping of rock specimens for testing of uniaxial tensile strength by high speed abrasive water jet: First experience, in Konečný (ed.): Eurock 2005 - Impact of Human Activity on the Geological Environment, London, Balkema 2005, pp 545-549.

[Soucek 2005] Soucek, K. The possibility of application of selected chemical grouting media to affect properties of carboniferous rock mass in coal mines (in Czech). Ph.D. Thesis. VSB - Technical University of Ostrava, 2005.

[Van Mier 2002] Van Mier, J. G. M. et al. Uniaxial tension test for the determination of fracture parameters of concrete: state of the art. Engineering Fracture Mechanics 69, 2002, pp 235-247.

[Vutukuri 1974] Vutukuri, V. S. et al. Handbook on Mechanical Properties of Rocks. Testing Techniques and Results – Vol. I. TRANS TECH Publications, Clausthal, Germany 1974, pp 281.

[Zeng 1994] Zeng, J., Samuel, W. and Thomas, K. Development of Parameter Prediction Model for Abrasive Waterjet Turning, in Allen, N.G. (ed.): Jet Cutting Technology: Applications and Opportunities; Proc. 12th intern. conf., Rouen, 25-27 October, 1994. Bedfordshire, BHR Group.

[Zhong 2002] Zhong, Z. W. et al. Turning of glass with abrasive waterjet. Materials and Manufacturing Processes 2002, Vol. 17, No. 3/2002, pp 339-349.

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