IT support for optimisation of abrasive water cutting process using the TOPSIS method

A Radomska-Zalas, A Perec and A Fajdek-Bieda

Jacob of Paradies University, Department of Technology, Teatralna 25, Gorzow Wlkp., Poland
aperec@ajp.edu.pl

Abstract. Modern production processes are becoming increasingly complex. At the same time, customers require high-quality products at the lowest price. This situation increases the importance of optimisation of production processes from the preparation of production to its implementation. Various methods of process optimisation have been devised to respond to the emerging phenomena including organisational aspects, device design, quality engineering and process automation. The TOPSIS method is used to make multi-criteria decisions. In this paper, a methodological study of this method was carried out, indicating conditions of applicability, assumptions and limitations, and the use of the TOPSIS method in the IT system supporting the optimisation of industrial processes on the example of waterjet cutting optimisation.

1. Introduction

In the production company, many activities are performed as a result of which input elements, such as materials, are transformed into output elements, i.e. the finished product. Production processes in the industrial environment are more and more complex and require the correlation of high quality of the product and the lowest possible price. The development of production processes led to the moment when optimisation took on a meaning, which denoted the drive towards lower production time and costs while maintaining the high quality of production. The work on optimisation methods considers not only organisational aspects but also the design of devices, their quality and automation of production processes. One of the forms integrating the mentioned factors is the IT system based on MCDM (Multiple criteria decision analysis) methods and algorithms of Decision Support Systems (DSS). There are also expert systems which seek the solution to the decision problem in logical reasoning with the use of an expert knowledge base. The source of knowledge is the analysis of processes. Such knowledge is important in intelligent systems, which use representation, understanding, design and implementation of knowledge. The dynamic development of technologies, products and requirements, however, shifts the emphasis away from the analysis of processes, and knowledge is often not used after making optimal decisions. It is the use of information systems that should facilitate the acquisition and processing of knowledge to optimise industrial processes.

Among the emerging production technologies, high-pressure water jet cutting is particularly attractive due to its environmental soundness [1] [2]. High-pressure water jet machining is one of the fastest developing advanced production technologies and is a preferred alternative to conventional material separation methods. This is largely due to the wide cutting possibilities of various materials [3], including multilayer materials of heterogeneous properties, as well as the precise cutting of a complex contour [4].

The optimisation of the cutting process with an abrasive water jet is supported by IT systems, which stems from the incapacity of the current models of prediction of abrasive water cutting effects to give
satisfactory results in a wide range of parameter changes, in particular regarding new materials. This means that extensive research is needed to extend the empirical database, which requires the use of IT tools along with methods known as Design of Experiment. One of the methods supporting the selection of optimal parameters for various technological processes is the TOPSIS approach. The article presents the general construction of an IT system and an example of using the incorporated TOPSIS method for the selection of best parameters for optimising abrasive waterjet cutting. The TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) was proposed in 1981 by Hwang and Yoon [5] and assumes identifying the best solution from a complete set of solutions – alternatives [6]. According to the TOPSIS methodology, the best solution is the one that has the shortest distance from the best, and at the same time the farthest from the worst solution [8]. In other words, it consists in comparing an analysed decision’s options with reference solutions: ideal solution non-ideal solution and assessing the distance between the variants and these solutions. As optimal, the chosen variant at the shortest distance from the ideal solution and the longest from the non-ideal one is chosen. The TOPSIS method algorithm consists of the following steps [7] [8]:

1. Establishment of a normalised decision matrix.
2. Determination of weighted normalised decision matrix.
3. Determining the evaluation of the weighted "ideal" solution and the weighty "non-ideal" solution.
4. Determining the distance from the weighted "ideal" and "non-ideal" solution.
5. Determination of relative distances from the weighted ideal solution.
6. Selection of the best variant.

The subsequent section of this work presents the results from analyses on the selection of optimal aluminium cutting parameters for the abrasive water jet technology using the TOPSIS.

2. Construction of an IT system to support process optimisation

Optimisation of production processes is the choice of the most advantageous solution, taking into account the key factors for an industrial enterprise, i.e. cost, time, product quality [9]. When designing an IT system supporting the optimisation of production processes, it is necessary to take into account the cost, time, quality of the product, but also such activities related to the production process and related factors as employees, machinery and equipment, storage or means of transport.

The design of the production optimisation support system was created based on the experience of companies gathered in the Lubuski Metal Cluster. Lubuski Metal Cluster needs a system that facilitates decision-making poorly structured at the strategic and tactical level of management. The main requirements for an optimisation decision support system are unit data retrieval, i.e. data extraction from collections. It was also necessary to ensure free access to and analysis of data, as well as to provide previously defined aggregate data. The result of the system's operation should be the preparation of projects of possible decisions and presenting the consequences of proposed decisions using calculation and simulation models.

To build the system, the quantitative and qualitative data was used, which made it possible to build a database and a database of methods that, thanks to artificial intelligence, allow the system to learn and adapt to changing data and changes in the organisation's environment. The main components of the system are:

- the user interface,
- a database and a database of methods that bring together the knowledge of the system,
- decision support module, which contains a description of the problem to be solved and
- enables the selection of artificial intelligence methods,
- a module for collecting data and transferring it to the database.

The project also assumes the need to consider the most important functions required by decision support systems, such as:

- a function that allows obtaining selected information from a database, spreadsheets, statistical data, historical data and other data sources available in the company. Acquiring information is the source of further analysis and is the basis for making decisions in the field of optimisation,
• a function identifying the problem, i.e. based on the specified data and specific input conditions indicating the place or area in the organisation that requires optimisation,
• conditional analysis function for the estimation of the probability of meeting the input conditions by the entered data and the suitability of this data for the process of optimisation of a given place or area in the enterprise,
• function that calculates the effects of certain decision options. This function makes it possible to estimate the effects of decisions made, considering the possibility of changing data or changes in the company's environment. Thanks to the use of such a function, the system user can work on various data and can make decisions supported by the analysis of these data,
• an optimisation function, which was recognised as the most important function, and which allows making decisions maximising or minimising the objective function without disturbing the set of input conditions. The result of the executed function is the presentation of several decision variants from which the user chooses the most advantageous variant.

Considering all input data and after analysing the problems of companies, the system project was created. The designed system supporting the optimisation of production processes is presented in Figure 1.

**Figure 1.** Design of the support system for the selection of optimisation process parameters (own study).

At the entrance to the system there is a user interface, by means of which data is put into the system, as well as by means of which the user is familiarised with the decision options to choose from. Another element of the system is its knowledge, which consists of a database and a database of methods. System knowledge is data entered into the system, but also those that the system collects as a result of learning. The system supports decision-making in a module using artificial intelligence methods (decision trees, neural networks, generic algorithms). This module uses the knowledge of the system. The output of the system is a decision to help the user in the optimisation process. The output data is passed on to users and at the same time, they are input data read into the database and method database as a base for system learning.

The designed system enables the integration of data from various levels and areas of the company, remembers the effects of decisions taken, as well as adapts to changing data and the environment. The system makes it possible to identify general problems that are easy to specify, as well as problems, including smaller-scale ones, that are difficult to determine. The system collects data from various levels and finds decision-makers at different levels in the organisation hierarchy.

It should be mentioned that the system supports decision-making, but the decision-maker supervises and controls each stage of the process. The decision-maker can finish work with the system at any stage. Thanks to the possibility of supporting all stages of decision-making, the system also gives the
opportunity to make many decisions often dependent on each other, and difficult to take because of different styles of decision-making by many decision-makers. In addition, the function of adapting to the changing environment of the system enables effective support of decision making. The decision is made faster, and at the same time exhibits high quality and accuracy. The proposed system adapts and learns, but also gives the opportunity to teach the decision-maker. System users learn the approach to planning and decision-making. Models that are part of the system give the possibility to apply different approaches and, consequently, different variants of the decision.

3. Investigation of the impact of the TOPSIS method on the selection of optimal parameters

Machining materials with a high-pressure abrasive stream is more complex than conventional machining methods. Water under high pressure, produced in a special high-pressure pump, is transformed inside the nozzle into a high-speed stream (amounting to 800 m/s), grabs and accelerates abrasive grains in the mixing chamber [10].

The addition of dry abrasive to the nozzle increases the cutting efficiency and, as a result, empowers the stream to cut any material [11] [12]. The most commonly used abrasive is garnet [13], but there are other natural and synthetic abrasives [14], such as crushed glass, olivine and aluminium [12] [15] [16]. The abrasive should be selected considering the relationship between nozzle life and workpiece performance [17] [18]. The results presented in the article refer to the less common choice – aluminium.

The article presents the process of testing the IT system while selecting the optimal parameters of the abrasive water cutting process [19] [20]. Two dependent output parameters of the process were introduced:

- **Width** – width of kerf. It is important that it is as long as possible, although the width is of minimal importance during a single cutting. It is acquired only in the case of a pattern/cutting of many elements from a material board. Width is expressed in [mm].
- **Rz** – one of the surface roughness parameters (quality). The coefficient should be as low as possible because then the quality of surface finish is high. Rz is expressed in [mm].
- In addition, three independent control parameters for the cutting process were introduced:
  - **Traverse speed** – feed. The speed of movement of the stream with respect to the workpiece material expressed in [mm/s].
  - **Pressure** – working pressure given in [MPa]
  - **Abrasive flow rate** – abrasive flow rate expressed in [g/s].

The TOPSIS described above was chosen as the method for selecting the optimal parameters. The TOPSIS method was employed to verify its suitability for the selection of water cutting process parameters. As the TOPSIS method is crucial in assigning weights to individual parameters, three options were considered:

- highest weight for **Width**, - highest weight for **Rz**, - equivalent **Width** and **Rz**.

The reason for the adoption of three possibilities is the will to examine whether and how the assignment of the above-mentioned weight for one criterion will affect the selection of optimal parameters. For each of the possible selections of weights, the study was conducted in six stages, the results of which are given below:

- **Establishing a normalised decision matrix.**

 Nine variants and two dependent criteria were adopted for the study. For each variant, independent criteria were assigned, the application of which produced a dependent criterion. The dependent criteria have been normalised by a quotient that follows the formula (1):

$$X_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

where:

- $X_{ij}$ – normalised j-criterion value in i-th option;
- $x_{ij}$ – real j-criterion value in i-th option;
- $m$ – number of possibilities.

A normalised decision matrix is provided in Table 1.
Table 1. Normalised decision matrix (own study).

| Traverse speed | Pressure | Abrasive flow rate | Rz | Width |
|----------------|----------|--------------------|-----|-------|
| [mm/s]         | [MPa]    | [g/s]              | [mm] | [mm] |
| 0.5            | 350      | 2                  | 13.61 | 1.05 |
| 0.5            | 300      | 1.5                | 14.43 | 0.95 |
| 0.5            | 250      | 1                  | 18.33 | 0.845|
| 0.75           | 350      | 2                  | 12.76 | 0.94 |
| 0.75           | 300      | 1.5                | 15.67 | 0.85 |
| 0.75           | 250      | 1                  | 14.49 | 0.75 |
| 1              | 350      | 1.5                | 19.52 | 0.85 |
| 1              | 300      | 1                  | 20.46 | 0.75 |
| 1              | 250      | 2                  | 16.38 | 0.75 |

- Determination of weighted normalised decision matrix.

Building a decision matrix, a probe was carried out for three possibilities:
- Greater importance of Width (0.75), smaller Rz (0.25);
- Greater importance of Rz (0.75), lower Width (0.25);
- The equal weight of Width (0.5) and Rz (0.5).

The normalised criteria values were multiplied by the weights. Table 2 presents the results for the three weighting allocation possibilities, obtained by means of calculations compliant with the formula (2):

\[ WX_{ij} = X_{ij} \times w_j \]  

where:

\( WX_{ij} \) = normalised weighted j-criterion value in i-th option;  
\( X_{ij} \) = normalised j-criterion value in i-th option;  
\( w_j \) = the weight given to the jth criterion.

Table 2. Weighted normalised decision matrix (own study).

| Traverse speed | Pressure | Abrasive flow rate | Rz | Width | Rz | Width | Rz | Width | Rz | Width |
|----------------|----------|--------------------|-----|-------|-----|-------|-----|-------|-----|-------|
| [mm/s]         | [MPa]    | [g/s]              | [mm] | [mm]  | [mm] | [mm]  | [mm] | [mm]  | [mm] | [mm]  |
| 0.5            | 350      | 2                  | 13.61 | 1.05  | 0.27690763 | 0.40459123 |
| 0.5            | 300      | 1.5                | 14.43 | 0.95  | 0.29359127 | 0.36605874 |
| 0.5            | 250      | 1                  | 18.33 | 0.845 | 0.37294026 | 0.32559961 |
| 0.75           | 350      | 2                  | 12.76 | 0.94  | 0.25961362 | 0.36220549 |
| 0.75           | 300      | 1.5                | 15.67 | 0.85  | 0.31882018 | 0.32752624 |
| 0.75           | 250      | 1                  | 14.49 | 0.75  | 0.29481202 | 0.28899374 |
| 1              | 350      | 1.5                | 19.52 | 0.85  | 0.39715187 | 0.32752624 |
| 1              | 300      | 1                  | 20.46 | 0.75  | 0.41627701 | 0.28899374 |
| 1              | 250      | 2                  | 16.38 | 0.75  | 0.33326576 | 0.28899374 |
• Determining the evaluation of the weighted "ideal" solution and the weighty "non-ideal" solution.

In the next step, PIS (Positive Ideal Solution) and NIS (Negative Ideal Solution) were calculated. PIS, or the "perfect" solution, contains the highest values of the maximised and the lowest minimised variables, NIS vice versa. The formulas (3) and (4) were used for calculations:

\[
PIS^+ = WX_1^+, WX_2^+, \ldots, WX_n^+ = \{\max_i WX_{ij}, \min_i WX_{ij}\}
\]

(3)

\[
NIS^- = WX_1^-, WX_2^-, \ldots, WX_n^- = \{\min_i WX_{ij}, \max_i WX_{ij}\}
\]

(4)

In Table 3, PIS and NIS values for the tested criteria are shown.

| Rz | Width | Ideal | | | | 0.75 | 0.25 | 0.25 | 0.75 | 0.5 | 0.5 | 0.5 |
|----|-------|-------|----|---|----|----|----|----|----|----|----|----|
| 0.75 | 0.555036 | 1.618365 | 1.665108 | 0.539455 | 0.83255403 | 0.80918247 |
| Non-ideal | 0.346151 | 1.155975 | 1.038454 | 0.385325 | 0.51922724 | 0.57798748 |

• Determining the distance from the weighted “ideal” and “non-ideal” solution

Subsequently, the distance of considered possibilities from the “ideal” and “non-ideal” solution was calculated. For this purpose, formulas (5) and (6) were used:

\[
d^+_i = \sqrt{\sum_{j=1}^{n}(WX_{ij}^+ - WX_{ij})^2}
\]

(5)

where:

\[d^+_i\] - distance from the “ideal” solution

\[
d^-_i = \sqrt{\sum_{j=1}^{n}(WX_{ij}^- - WX_{ij})^2}
\]

(6)

where:

\[d^-_i\] - distance from the “non-ideal” solution

The distance of the variants from the “ideal” solution is presented in Table 4, and from “non-ideal” in Table 5.

Table 4. The distance from the weighted "ideal" solution (own study).

| Traverse speed [mm/s] | Pressure [MPa] | Abrasive flow rate [g/s] | Rx Width [mm] | 0.75 | 0.25 | 0.25 | 0.75 | 0.5 | 0.5 | 0.5 |
|-----------------------|---------------|-------------------------|---------------|------|------|------|------|------|------|------|
| 0.5 | 350 | 2 | 13.61 | 1.05 | 0.185825842 | 0.557477526 | 0.278738763 |
| 0.5 | 300 | 1.5 | 14.43 | 0.95 | 0.224754972 | 0.493425014 | 0.257189005 |
| 0.5 | 250 | 1 | 18.33 | 0.845 | 0.321206507 | 0.202834784 | 0.180197123 |
| 0.75 | 350 | 2 | 12.76 | 0.94 | 0.269030799 | 0.202834784 | 0.180197123 |
| 0.75 | 300 | 1.5 | 15.67 | 0.85 | 0.334528415 | 0.403142171 | 0.248490233 |
| 0.75 | 250 | 1 | 14.49 | 0.75 | 0.48993201 | 0.509721464 | 0.335359662 |
| 1 | 350 | 1.5 | 19.52 | 0.85 | 0.309312915 | 0.128103799 | 0.15880535 |
| 1 | 300 | 1 | 20.46 | 0.75 | 0.462389982 | 0.154129994 | 0.231194991 |
| 1 | 250 | 2 | 16.38 | 0.75 | 0.475452339 | 0.366073685 | 0.28463063 |
Table 5. The distance from the weighted "non-ideal" solution (own study).

| Traverse speed [mm/s] | Pressure [MPa] | Abrasive flow rate [g/s] | Rz Width [mm] | Rz Width [mm] | Rz Width [mm] | Rz Width [mm] |
|----------------------|----------------|--------------------------|---------------|---------------|---------------|---------------|
| 0.5                  | 350            | 2                        | 13.61         | 1.05          | 0.462964575. | 0.168941943  | 0.233767951  |
| 0.5                  | 300            | 1.5                      | 14.43         | 0.95          | 0.311571227  | 0.170381725  | 0.168445767  |
| 0.5                  | 250            | 1                        | 18.33         | 0.845         | 0.210408433  | 0.455926558  | 0.23818414   |
| 0.75                 | 350            | 2                        | 12.76         | 0.94          | 0.292846988  | 0.097615663  | 0.146423494  |
| 0.75                 | 300            | 1.5                      | 15.67         | 0.85          | 0.173170165  | 0.242334933  | 0.141282265  |
| 0.75                 | 250            | 1                        | 14.49         | 0.75          | 0.046931198  | 0.140793594  | 0.070396797  |
| 1                    | 350            | 1.5                      | 19.52         | 0.85          | 0.239553479  | 0.552546731  | 0.285667807  |
| 1                    | 300            | 1                        | 20.46         | 0.75          | 0.208884523  | 0.626653570  | 0.313326785  |
| 1                    | 250            | 2                        | 16.38         | 0.75          | 0.098202854  | 0.294608561  | 0.147304281  |

- Determination of relative distances from the weighted ideal solution and selection of the best variant.

In the last step, the relative proximity coefficient of the decision variants to the ideal solution was determined; formula (7) was used for this purpose:

$$d_i = R_{D_i} = \sqrt{d^+ + d^-}$$

On the basis of the obtained values of the relative closeness coefficient of decision variants, assuming that the higher the RDi value the better the decision-making variant, the system generated a ranking of variants, which is presented in Table 6.

Table 6. Relative distances from the weighted ideal solution and selection of the best variant (own study).

| Traverse speed [mm/s] | Pressure [MPa] | Abrasive flow rate [g/s] | Rz Width [mm] | Rz Width [mm] | Rz Width [mm] | Rz Width [mm] | Rz Width [mm] |
|----------------------|----------------|--------------------------|---------------|---------------|---------------|---------------|---------------|
| 0.5                  | 350            | 2                        | 13.61         | 1.05          | 0.286148970  | 9             | 0.767431973  | 3             | 0.543873388  | 6             |
| 0.5                  | 300            | 1.5                      | 14.43         | 0.95          | 0.419063944  | 8             | 0.74332631  | 4             | 0.604248107  | 5             |
| 0.5                  | 250            | 1                        | 18.33         | 0.845         | 0.604208954  | 5             | 0.307903289 | 7             | 0.43070079  | 7             |
| 0.75                 | 350            | 2                        | 12.76         | 0.94          | 0.47880661   | 7             | 0.865693459 | 1             | 0.689132232 | 2             |
| 0.75                 | 300            | 1.5                      | 15.67         | 0.85          | 0.658911465  | 4             | 0.624564634 | 5             | 0.637526338 | 4             |
| 0.75                 | 250            | 1                        | 14.49         | 0.75          | 0.912582577  | 1             | 0.783565972 | 2             | 0.826048028 | 1             |
| 1                    | 350            | 1.5                      | 19.52         | 0.85          | 0.56354865   | 6             | 0.188207888 | 8             | 0.357288956 | 9             |
| 1                    | 300            | 1                        | 20.46         | 0.75          | 0.688823998  | 3             | 0.19740425  | 9             | 0.424583354 | 8             |
| 1                    | 250            | 2                        | 16.38         | 0.75          | 0.828812055  | 2             | 0.554084338 | 6             | 0.658966486 | 3             |

4. Results and discussion

The article presents the results that the IT system returned for the nine possible combinations of input parameters introduced. Two dependent and three independent criteria for process optimisation of abrasive water jet cutting were introduced into the system. Because the method is important for the weights assigned to a particular criterion, a test was carried out for three possibilities, i.e. more weight was assumed for Width, then higher for Rz, and the last possibility was equal weights. Table 6 shows the results for given possibilities. Figure 2 presents the values of dependent parameters and position results for individual options.
When analysing the three highest classified parameters, one option is particularly worth the attention, i.e. 0.75 for traverse speed, 250 for pressure and 1 for abrasive flow rate, which gives 14.49 for Rz and 0.75 for Width. The indicated result, regardless of the assigned weights, takes into account the recommendation that Width and Rz should be as small as possible. Despite the large dispersion for the remaining results, this one is highly indicated for three options.

5. Summary and conclusion
Although the TOPSIS method works best for multiple criteria, even with two gives satisfactory results. The general assessment of the results leads to the conclusion that the use of the TOPSIS method enables the selection of optimal process parameters that significantly affect the test process, and at the same time allows the user to omit those factors that have a negligible impact on the results. It can simplify the test process very much, reducing the time to obtain reliable results and lowering the cost of testing, because it reduces the number of tests required. However, it should be remembered that one of the limitations of this method is the need to give weight, which is usually subjective.

The TOPSIS method does not require IT support, but the use of an IT system as a tool supporting the calculation process is important. It enables the creation of a knowledge base, which in the context of repeatability of research will allow the decision-makers to increase the correctness of the final results, as well as to compare the results achieved for various multi-criteria analysis methods. It is also important to use artificial intelligence mechanisms in the system. An IT system equipped with the AI mechanisms gives the possibility of repeated use in making a concrete decision, considering different input states each time. Such a system thus becomes a universal tool with a simulation character. It should be added that the use of an expert system, particularly in the optimisation of production processes, may have an impact on shortening the entire process cycle, which gives the opportunity to analyse a larger number of cases, and in combination with the possibility of using historical data increases the efficiency and accuracy of the decisions taken.

6. References
[1] Patyk R et al. 2018 Experimental and numerical researches of duplex burnishing process in aspect of achieved productive quality of the product AIP Conference Proceedings 1960 070021 doi:10.1063/1.5034917
[2] Kukiela L et al. 2016 Analysis of the States of Deformation and Stress in the Surface Layer of the Product after the Burnishing Cold Rolling Operation Materials Science Forum 862 278-87
[3] Wessels V, Grigoryev A, Dold C and Wyen C-F 2012 Abrasive waterjet machining of three-dimensional structures from bulk metallic glasses and comparison with other techniques J. Mater. Res. 27(8) 1187–92 doi: 10.1557/jmr.2012.36

[4] Ćojašić Ž, Petković D, Shamshirband S, Tong Ch W, Sudheer Ch, Janković P, Dućić N and Baralić J 2016 Surface roughness prediction by extreme learning machine constructed with abrasive water jet Precision Engineering 43 86–92 doi: 10.1016/j.precisioneng.2015.06.013

[5] Hwang C L and Yoon K 1981 Multiple Attribute Decision Making Methods and Applications (Springer-Verlag) doi:10.1007/978-3-642-48318-9

[6] Decui L, Zeshui X, Dun L and Yao W 2018 Method for three-way decisions using ideal TOPSIS solutions at Pythagorean fuzzy information Information Sciences 435 282-95

[7] Kasprzak D 2018 Przedziałowa metoda TOPSIS dla grupowego podejmowania decyzji Optimum. Economic Studies 4(94) 256-73 doi:10.15290/oes.2018.04.94.19

[8] Yuvaraj N and Pradeep Kumar M 2014 Multiresponse Optimization of Abrasive Water Jet Cutting Process Parameters Using TOPSIS Approach Materials and Manufacturing Processes 30(7) 882-89 doi:10.1080/10426914.2014.994763

[9] Távođova M, Kalincova D and Slovakova I 2018 Evaluation of Some Parameters of Hard Surfacing Treatment of the Functional Surfaces of Forestry Tools Management Systems in Production Engineering 26(4) 222-26

[10] Valiček J, Hloch S and Kozak D 2009 Surface geometric parameters proposal for the advanced control of abrasive waterjet technology The International Journal of Advanced Manufacturing Technology 41(3-4) 323–28

[11] Producing GMA in Australia GMA Garnet Australia Accessed: 18-Mar-2019 available: https://www.gmagarnet.com/en-gb/about-gma/producing-gma-australia

[12] Cenac F, Zitoune R, Collombet F and Deleris M 2015 Abrasive water-jet milling of aeronautical aluminium 2024-T3 Proceedings of the Institution of Mechanical Engineers Part L: Journal of Materials Design and Applications 229(1) 29–37 doi:10.1177/1464420713499288

[13] Aydin G, Kaya S and Karakurt I 2017 Utilization of solid-cutting waste of granite as an alternative abrasive in abrasive waterjet cutting of marble Journal of Cleaner Production 159 241–47

[14] Sriragen A K and Sathiya P 2017 Optimisation of Process Parameters for Gas Tungsten Arc Welding of Incoloy 800HT Using TOPSIS Materials Today: Proceeding 4 2031-2039

[15] Perec A 2016 Abrasive Suspension Water Jet Cutting optimization using orthogonal array design Procedia Engineering 149 366–73

[16] Supriya S B and Srinivas S 2018 Machinability Studies on Stainless Steel by Abrasive Water Jet – Review Materials Today: Proceedings 5 2871–76

[17] Perec A, Pude F, Kaufeld M and Wegener K 2017 Obtaining the selected surface roughness by means of mathematical model based parameter optimization in Abrasive Waterjet Cutting J of Mech. Eng. 63(10) 606–13

[18] Klinik D, Gánovská B, Hloch S, Monka P, Monková K and Hutyrová Z 2015 On-line monitoring of technological process of material abrasive water jet cutting. On-line praèenje tehnološkog postupka rezanja materijala abrazivnim vodenim mlazom Technický výskum 22(2) 351–57

[19] Perec A and Radomskas-Zalas A 2019 Modeling of abrasive water suspension jet cutting process using response surface method AIP Conference Proceedings 2078 020051 doi:10.1063/1.5092054

[20] Perec A, Radomskas-Zalas A, Bieda A, Musial W, Pražmo J, Sobczak R and Nagnajewicz S Study into abrasive water jet machining of corundum based ceramics. Lecture Notes in Mechanical Engineering Advances in Manufacturing Engineering and Materials (to be published)