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Use of the Simple Multicriteria Decision-Making (MCDM) Method for Optimization of the High-Alloy Steel Cutting Process by the Abrasive Water Jet

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ABSTRACT

In the case of advanced manufacturing technologies, which include Abrasive Water Jet Machining, optimization of control parameters is necessary to achieve appropriate efficiency and quality. One of the optimization methods used in the presented research is SAW, from the Multi-Criteria Decision Making (MCDM) group. In multi-criteria decision-making (MCDM) situations, the criterion weights are crucial components that have a big impact on the outcomes. A novel technique called MEREC (MEthod based on the Removal Effects of Criteria) was presented to find the objective weights of the criteria. The research covered cutting high-alloy steel using AWJ, under the Design of Experiment (DoE) within the L9 orthogonal table. Abrasive flow rate, pressure, and feed were selected as control parameters. The cutting depth (beneficial) and the roughness of the cut surface Sa (non-beneficial) were taken as the output parameters. The result of the research is the determination of the impact of individual control parameters and the determination of a set of control parameters from the point of view of efficiency and quality.

1. Introduction

The abrasive water jet (AWJ) cutting is an advanced manufacturing technology [1] for precisely cutting a wide range of materials [2] using a high-pressure jet of water with an abrasive material [3]. Advanced manufacturing methods are characterized by more control parameters that influence the processing effect in comparison to conventional machining technology [4]. Therefore, it is desirable to modeling [5] and optimization [6,7] such techniques. Compared to other unconventional contour cutting technologies, only Abrasive Water Jet (AWJ) and fiber laser cutting technology [8] progressively appear as the most suitable selection for modern industrial manufacturing.

The processing by AWJ is very comprehensive because it can treat different types of materials, such as rocks [9,10], glass [11], hard metals [12,13] composites [14,15] special structural 3D materials [16], heavy-to-machining metals [17], and even superalloys [18].

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AWJ cutting process optimization studies based on MCDM employing the Technique for Order Preference by Similarity Ideal Solution (TOPSIS) method are described by Yuvaraj *et al.,* [19]. Pressure, traverse rate, abrasive flow rate, and standoff distance are among the process control parameters that are tuned using multiple response output parameters, such as surface roughness (Ra), depth of penetration (DOP), cutting rate (CR), taper cut ratio (TCR), and top kerf width (TKW). With combinations of the AWJ cutting process settings, higher DOP and CR and lower Ra, TCR, and TKW were attained, according to the optimum results produced from this approach.

Also, Khan *et al*., [20] described the implementation of multi-criteria decision-making (MCDM) of selected modern manufacturing processes (MMPs), particularly Abrasive Water Jet Machining. Using the TOPSIS approach, the results were optimized to get the optimal parametric combination of cutting parameters. It was noted that the outcomes obtained using the TOPSIS method were nearly identical to those obtained by earlier researchers.

The two methods for multi-objective optimization—WASPAS and MOORA—were presented by Reddy et al., [21] and they proved that the rankings of both MCDM approaches were identical. On MRR and surface finish, traverse speed and abrasive mass flow rate were statistically significant. Influence on kerf width, standoff distance, and the two parameters was also significant. It was verified by the SEM observation that a rougher surface was created with a higher abrasive flow rate.

In most of the reports published so far, the input or decision matrix served as the foundation for the objective weighting techniques applied in the MCDM methods This work, in contrast to the other methods, attempts to use a unique objective weighting technique called MEREC. It is based on the relationship between the decision matrix or input and its impact on the performance of alternatives or the output and thus the existing research gap was filled. This paper aims to present the basics of using this MCDM method optimization with the MEREC weights factor determination procedure by example of the high-alloy steel processing by AWJ.

2. Methodology and Materials

2.1 AWJ machining

The research was realized on a test rig based on the OMAX 60120 waterjet machining center. They engaged in cutting the high-alloy steel samples by leading the AWJ perpendicularly (Figure 1) and moving it with the defined traverse speed.

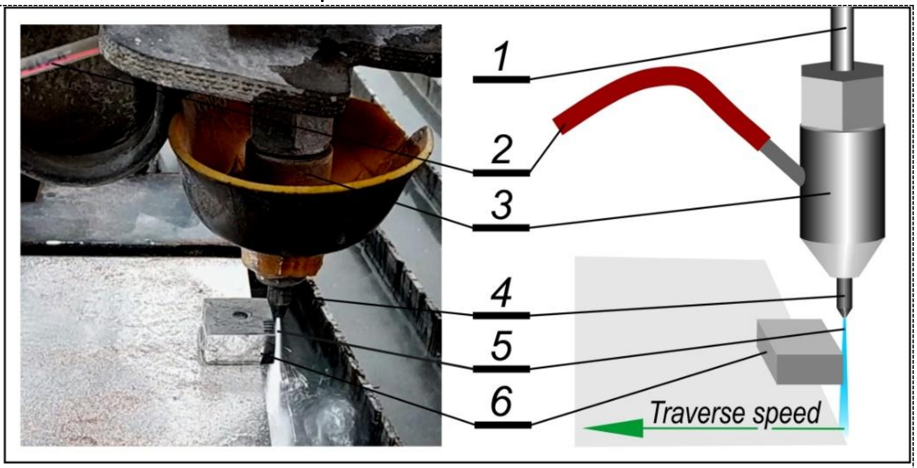

Fig. 1. Real view and schematic of AWJ cutting process: 1-water inlet, 2-abrasive inlet, 3-cutting head, 4-focusing tube, 5-AWJ, 6-target material

The AWJ cutting process was carried out at the following control factors:

- Working pressure: 360 - 400 MPa,
- Cutting speed: 50 - 250 mm/min,
- The abrasive mass flow: 250 - 450 g/min,
- Abrasive material; J80A garnet #80 (from crushed rock),
- Water nozzle / Focusing tube ID: 0.30/0.76 mm,
- Stand-off distance: 3 mm.

Maximum cutting depth (Hmax) measurements were used to evaluate the efficiency of the cutting process. This output parameter was assigned to beneficial factors. The surface roughness Sa was used to assess the quality. It is included in the group of non-beneficial factors. Details of these parameters are presented in Figure 2. Side surface roughness measurements conducted in the middle of the cutting are about 2.85 mm x 2.85 mm in stitching mode (elemental area 0.95 mm x 0.95 mm) on Olympus DSX1000 3D microscope. The measurement area was chosen in the middle of the useful cutting depth zone. The useful cutting depth is approximately half the maximum depth Hmax. In analysis of surface roughness Gaussian filter was used.

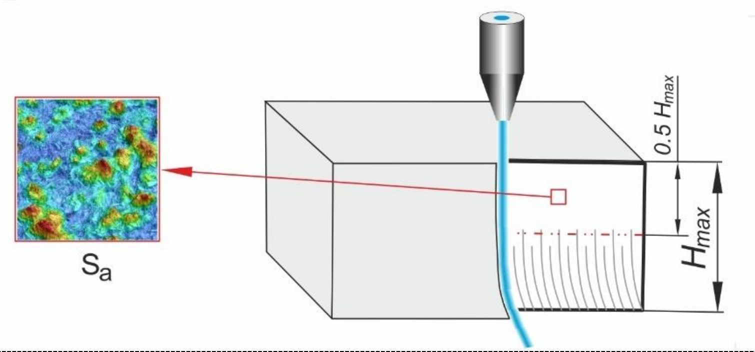

Fig. 2. Schematic view of cutting process output parameters

2.2 Cutting material

1.4923, also known as X22CrMoV12-1, is a high-alloy steel with the addition of chromium, molybdenum, and vanadium, which makes it widely used in the machinery and energy industries. It is used for structural parts of steam turbines, pressure, and steam boilers, and heat-resistant screws. A special feature of the 1.4923 grade is its heat resistance up to approx. 600°C. It is characterized by exceptional strength, hardness, and corrosion resistance, which makes it an ideal choice also in the machinery industry and the production of tools.

This material is weldable but requires specialized techniques and additional materials. This material is suitable for hardening and tempering as well as normalization. The quenching process usually takes place at temperatures of 910-960°C, followed immediately by tempering in the range of 660-710°C.

The machinability of this steel is directly associated with its hardness. Still, it can be obtained that the treatment parameters will differ depending on the structure/hardness of the steel using even coated hard materials cutting tools.

2.3 Abrasive material

In the tests conducted, garnet was used as an abrasive material. Garnet is a group of silicate minerals used since the Bronze Age as gemstones and abrasives. They come in a variety of colors, but they are most known for their deep red hues. Garnet is not a single mineral but a group of related minerals that share a common crystal structure and similar physical properties. The general chemical formula for garnets is following: $A_3B_2(SiO_4)_3$, where A and B are different metal ions.

Garnet abrasive material is a commonly used material in water jet cutting due to its hardness, durability, and sharp edges, which make it highly effective at cutting through a wide range of materials. Among the various varieties of this mineral, the most frequently used in AWJ processing is almandine, due to its hardness (7.5-8.0 on the Mohs scale) and cost-effectiveness. The chemical formula for almandine is as follows: $Fe_3Al_2(SiO_4)_3$.

An additional advantage of almandine is its recyclability [22]. Almandine garnet grains can often be recycled and reused, even 5 times [23], and good environmental impact because garnet is a natural mineral and is generally considered environmentally friendly compared to a lot of synthetic abrasives [24].

The J80A garnet used in the tests comes from a deposit in Jiangsu Province, China, and was produced by Lianyungang Jinhong Mining [25]. An example of the shape of an isolated grain is shown in Figure 3. The isometric shape of the grain and its sharp edges can be observed. The particle grain distribution is shown in the graph in Figure 4. The distribution is close to normal with the predominance of grains ranging in size from 212 to 250 µm.

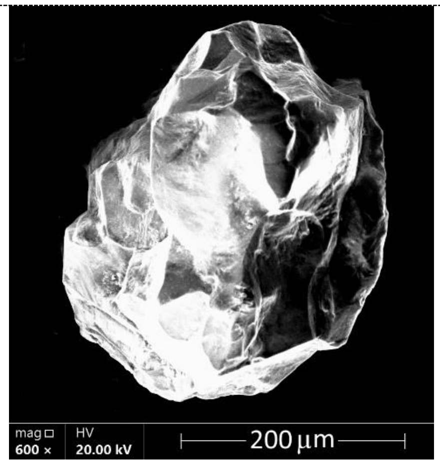

Fig. 3. SEM view of example single J80A garnet grain

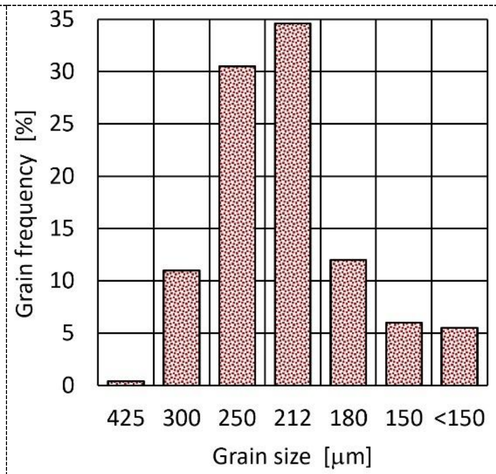

Fig. 4. Grain size distribution of J80A garnet abrasive material

2.4 Simple Additive Weighting Method (SAW)

Simple Additive Weighting (SAW) is a multi-criteria procedure established on the weighted summation idea. It is one of the simplest methods used to solve multiple attribute decision challenges. The benefit of this simple concept method is to find the level of weighted performance ratings for every alternative on all attributes [26]. SAW needs an operation of normalizing the decision matrix (*X*) to a similar scale for all the ratings of existing alternatives. In this method two types of attributes are recognized: benefits and costs (non-benefits) criteria. The difference between these criteria is the selection basis when making decisions. The calculation by the SAW method was conducted in the following steps:

The building of the decision array

Every alternate indicator or value for each criterion is shown in this array. Expression x_{ij} determines the elements of this array. The following is the decision array's form *X* for n choices and m criteria:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1j} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2j} & \dots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{im} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{nj} & \dots & x_{nm} \end{bmatrix} \tag{1}$$

Decision array normalization

An array normalization is a transformation to scale that can be compared with all the ratings of existing alternatives. This method has two attributes, benefits and cost criteria. For normalization of the decision array (*X*) using the simple linear normalization to scale the elements. Each element of the normalized array was described as r_{ik}^{x}. In case when *B* expresses of beneficial criteria set, and *N* expresses the non-beneficial criteria set, for normalization use the following equation:

$$r_{ij} = \begin{cases} \frac{\min_k x_{kj}}{x_{ij}}, \; if \; j \in B \\ \frac{x_{ij}}{\max_k x_{kj}}, if \; j \in N \end{cases} \tag{2}$$

Where r_{ij} is the normalized efficiency ratings of alternatives A_i on attributes C_j, i = 1,2, ... ,m and j = 1,2, ... , n. The preference value for every alternative (V_i) is the following:

$$V_i = \sum_{j=1}^{n} w_j \cdot R_{ij} \tag{3}$$

The bigger V_i level informs, that the A_i is better.

2.5 Removal Effects of Criteria Method.

The key element of optimization using MCDM methods is the proper determination of the parameter weight. For this purpose, it was used the MEthod of Removal Effects of Criteria (MEREC) to establish the criteria weights. The MEREC utilizes each criterion's removal effect on the value of alternatives for choosing criteria weights. Bigger weights are granted to the criteria with higher effects on the achievement. In this research, a plain logarithmic measure was used with equal weights to calculate alternatives' performances. To recognize the effects of removing each criterion, the absolute deviation measure was used. This parameter underlines the difference between the overall alternative's efficiency and its efficiency in removing a criterium. The calculation of target weights by MEREC was carried out in the following steps:

The building of the decision array

It shows all alternative indicators or values of every criterion. The components of this array are determined by x_{ij}, and positive ($x_{ij} > 0$). For *n* alternatives and *m* criteria, the form of the decision-array is identical as Eq. (1).

Decision array normalization

For normalization of the decision array (N) using the simple linear normalization to scale the elements. Each element of the normalized array was described as n_{ik}^{x}. In case when *B* expresses of beneficial criteria set, and *N* expresses the non-beneficial criteria set, for normalization use the following equation:

$$n_{ik}^{x} = f(x) = \begin{cases} \frac{\min_k x_{kj}}{x_{ij}}, \ if\ j \in B \\ \frac{x_{ij}}{\max_k x_{kj}}, if\ j \in N \end{cases} \quad (3)$$

The normalization process is similar but different from the process used in other methods for example WASPAS [27]. Here, should transform all the criteria into the minimization type [28].

Overall performance calculation

For the overall performance, the calculation was introduced of the alternatives (S_i) the logarithmic measure with equivalent criteria weights to acquire the alternatives' overall performances. The following equation was used for this calculation:

$$S_i = \ln\left(1 + \left(\frac{1}{m}\sum_j \left|\ln\left(n_{ij}^{x}\right)\right|\right)\right) \quad (4)$$

Alternatives Performance Calculation

In this step, too the logarithmic measure was used but the calculation was conducted on removing each criterium separately. Therefore, we have m sets of performances associated with *k* criteria. If denoted by S'_{ij} the overall performance of *i*-th alternative concerning the removal of *j*-th criterion. The following equation was used for the calculations:

$$S'_{ij} = \ln\left(1 + \left(\frac{1}{m}\sum_{k,k\neq j}\left|\ln\left(n_{ik}^{x}\right)\right|\right)\right) \quad (5)$$

Summation of absolute deviations

In this step, was calculated the removal effect of the *j*-th criterion based on the values obtained from previous steps. If E_j describes the results of removing *j*-th criterion, its values can be calculated by the following formula:

$$E_j = \sum_i \left|S'_{ij} - S_i\right| \quad (6)$$

End weights criteria establishing

In this step, each criterion's target weight was computed using the previous step's removal results (E_j). If w_j describes the weight of the *j*-th criterion for its calculation the following equation was utilized:

$$w_j = \frac{E_j}{\sum_k E_k} \quad (7)$$

3. Results and discussion

Table 1 provides the results of the of the tests. The detailed calculation procedure of Simple Additive Weighting (SAW) is described in section 2.4. To determine criteria weights, the MEREC method was used, according to the procedure, detailed described in detail in the 2.5 subchapter.

To show the relationships between the variables (control parameters) and the responses the factorial plots were used. Figure 5 presented the dependence of the cutting depth and Figure 6 the dependence of the surface roughness on the process control parameters.

Table 1
Results of the tests

	AFR [g/min]	Pressure [MPa]	Vp [mm/min]	Beneficial	Non-beneficial	Normalized		A_i	Rank
				Hmax [mm]	Sa [μm]	Hmax	Sa		
1	250	360	50	8.47	3.14	0.9098	0.9586	0.9396	3
2	250	380	150	5.16	3.54	0.5542	0.8503	0.7348	4
3	250	400	250	3.61	4.1	0.3878	0.7341	0.5990	8
4	350	360	150	4.91	4.29	0.5274	0.7016	0.6337	5
5	350	380	250	3.51	5.83	0.3770	0.5163	0.4620	9
6	350	400	50	9.31	3.24	1.0000	0.9290	0.9567	2
7	450	360	250	3.54	3.87	0.3802	0.7778	0.6227	7
8	***450***	***380***	***50***	***9.02***	***3.01***	***0.9689***	***1.0000***	***0.9879***	***1***
9	450	400	150	5.59	4.63	0.6004	0.6501	0.6307	6

As a result, weights were obtained for the maximum cutting depth, w_{Hmax}=0.39, and for the surface roughness, w_{Sa}=0.61 (Table 2). Based on the A_i index, the ranking of all alternatives was calculated. Alternative No. 8 took first place, as marked in bold italics (Table 1).

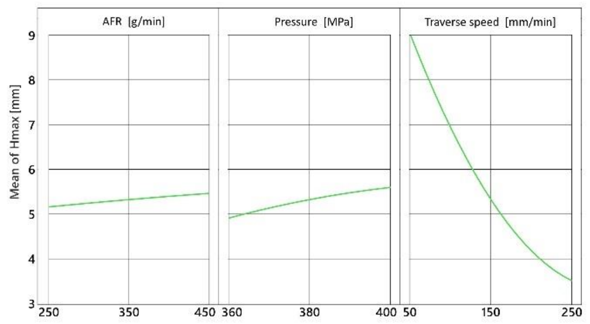

Fig. 5. Factorial Plots for cutting depth Hmax

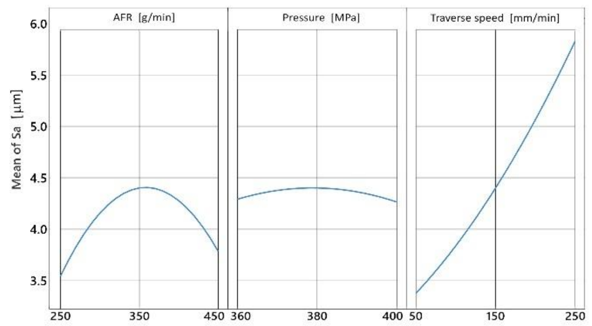

Fig. 6. Factorial Plots for surface roughness Sa

This corresponds to a set of the following control parameters: abrasive flow equal to 450 g/min, working pressure equal to 380 MPa, and traverse speed equal to 50 mm/min. Under these levels of control parameters, the output parameters were equal appropriately: cutting depth Hmax = 9.02 mm and surface roughness Sa = 3.01 μm.

Table 2
Calculation effects of factor weight

	Normalized		S_i	S'_{ij}		E_j		w_{Hmax}	w_{Sa}
	Hmax	Sa		Hmax	Sa	Hmax	Sa		
1	0.4144	0.5386	0.9396	0.2696	0.3650	0.1116	0.2070		
2	0.6802	0.6072	0.7348	0.2227	0.1762	0.1175	0.0710		
3	0.9723	0.7033	0.5990	0.1621	0.0139	0.1287	0.2769		
4	0.7149	0.7358	0.6337	0.1427	0.1551	0.0397	0.0273		
5	1.0000	1.0000	0.4620	0.0000	0.0000	0.4055	0.4055		
6	0.3770	0.5557	0.9567	0.2575	0.3973	0.0670	0.2067		
7	0.9915	0.6638	0.6227	0.1864	0.0042	0.0970	0.2792		
8	0.3891	0.5163	*0.9879*	0.2856	0.3866	0.0919	0.1928		
9	0.6279	0.7942	0.6307	0.1091	0.2092	0.0431	0.0570		
								0.3901	***0.6099***

An example of the intersection effect at this level of control parameters is shown in Figure 7 (optical microscope view) and Figure 8 (SEM view). The particular signs of erosion by the abrasive grains, are here visible in the shape of parallel tracks of micro-cutting could be observed. Moreover, the crack initiation sites and their expansion can be seen.

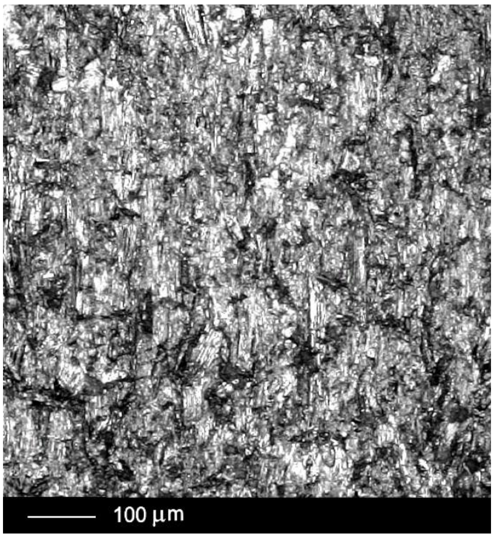

Fig. 7. Sample optical view of the cut surface

Fig. 8. Sample SEM view of the cut surface

4. Conclusions

High alloy steel X22CrMoV12-1 is tough to machining by the common treatment methods and therefore the AWJ technique was chosen for its machining. The study was performed to determine the influence of the most important machining control parameters constraints, pressure, abrasive flow rate, and traverse speed on example output parameters such as cutting depth and surface roughness. Multicriterial optimization by Simple Additive Weighting (SAW) was carried out based on the obtained results.

Determination of criteria weights is a key function in an MCDM process. The initial data defined in the MCDM problem-solving array support objective criteria weights. A new objective weighting method, called MEREC, was confirmed usefulness in this research and based on the removal effects of criteria on alternatives' performances considered a measure for weighting. It is a novel perspective on the determination of objective criteria weights.

Based on both points of view (performance and quality) tested in multi-optimization, the best effects in the form of large cutting depth and low roughness were obtained for the highest abrasive flow of 450 g/min, middle pressure of 380 MPa and the lowest traverse speed of 50 mm/min.

In further research, it is planned to use this very effective method of determining MEREC weights in other MCDM multiple optimization methods.

Author Contributions

The individual contributions of authors: Conceptualization, A.P. and E.K.; methodology, A.R-Z.; software, E.K.; validation, A.R-Z., E.K. and A.P.; formal analysis, A.R-Z.; investigation, E.K.; resources, A.P.; data curation, A.R-Z; writing—original draft preparation, A.P.; writing—review and editing, A.R-Z.; visualization, A.P.; supervision, A.R.-Z.; project administration, E.K.; funding acquisition, A.R-Z.
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Data Availability Statement
The study did not report any additional data.

Conflicts of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Hashish, M. (2024). Abrasive Waterjet Machining. Materials, 17(13), Article 13. https://doi.org/10.3390/ma17133273
[2] Perec, A., Radomska-Zalas, A., Fajdek-Bieda, A., & Pude, F. (2023). Process Optimization by Applying the Response Surface Methodology (RSM) to the Abrasive Suspension Water Jet Cutting of Phenolic Composites. Facta Universitatis, Series: Mechanical Engineering, 21(4), Article 0. https://doi.org/10.22190/FUME211123010P
[3] Perec, A., Radomska-Zalas, A., Fajdek-Bieda, A., & Kawecka, E. (2022). Efficiency of Tool Steel Cutting by Water Jet with Recycled Abrasive Materials. Materials, 15(11), 3978. https://doi.org/10.3390/ma15113978
[4] Radomska-Zalas, A. (2023). Experimental Research on the Use of a Selected Multi-Criteria Method for the Cutting of Titanium Alloy with an Abrasive Water Jet. Materials, 16(15), 5405. https://doi.org/10.3390/ma16155405
[5] Szada-Borzyszkowska, M., Kacalak, W., Banaszek, K., Pude, F., Perec, A., Wegener, K., & Królczyk, G. (2024). Assessment of the effectiveness of high-pressure water jet machining generated using self-excited pulsating heads. The International Journal of Advanced Manufacturing Technology. https://doi.org/10.1007/s00170-024-14040-6
[6] Bhoi, N. K., Singh, H., Pratap, S., & Jain, P. K. (2022). Chemical reaction optimization algorithm for machining parameter of abrasive water jet cutting. OPSEARCH, 59(1), 350–363. https://doi.org/10.1007/s12597-021-00547-z
[7] Perec, A., & Musial, W. (2021). Multiple Criteria Optimization of Abrasive Water Jet Cutting Using Entropy-VIKOR Approach. In S. Hloch, D. Klichová, F. Pude, G. M. Krolczyk, & S. Chattopadhyaya (Eds.), Advances in Manufacturing Engineering and Materials II (pp. 50–62). Springer International Publishing. https://doi.org/10.1007/978-3-030-71956-2_5
[8] Madić, M., Jovanović, D., & Janković, P. (2024). Fiber Laser Cutting Technology: Pilot Case Study in Mild Steel Cutting. Spectrum of Mechanical Engineering and Operational Research, 1(1), Article 1. https://doi.org/10.31181/smeor1120241
[9] Perec, A., Radomska-Zalas, A., & Fajdek-Bieda, A. (2022). Modeling of High Pressure Abrasive Water Jet Cutting of Marble. Facta Universitatis, Series: Mechanical Engineering, 20(1), 145–156. https://doi.org/10.22190/FUME210203037P
[10] Kawecka, E. (2024). The use of metaheuristic optimization algorithm in abrasive water jet machining of white marble. AIP Conference Proceedings, XIV International Conference Electromachining 2023, 020015. https://doi.org/10.1063/5.0203448
[11] Sutowska, M., Kapłonek, W., Pimenov, D. Y., Gupta, M. K., Mia, M., & Sharma, S. (2020). Influence of Variable Radius of Cutting Head Trajectory on Quality of Cutting Kerf in the Abrasive Water Jet Process for Soda–Lime Glass. Materials, 13(19), 4277. https://doi.org/10.3390/ma13194277
[12] Radomska-Zalas, A., Perec, A., & Fajdek-Bieda, A. (2019). IT support for optimisation of abrasive water cutting process using the TOPSIS method. IOP Conference Series: Materials Science and Engineering, 710, 012008. https://doi.org/10.1088/1757-899X/710/1/012008
[13] Perec, A., Musial, W., Prazmo, J., Sobczak, R., Radomska-Zalas, A., Fajdek-Bieda, A., Nagnajewicz, S., & Pude, F. (2021). Multi-criteria Optimization of the Abrasive Waterjet Cutting Process for the High-Strength and Wear-Resistant Steel Hardox®500. In D. Klichová, L. Sitek, S. Hloch, & J. Valentinčič (Eds.), Advances in Water Jetting (pp. 145–154). Springer International Publishing. https://doi.org/10.1007/978-3-030-53491-2_16

[14] Hlaváček, P., Sitek, L., Klichová, D., & Bodnárová, L. (2019). Effects of Abrasives During Accelerated Simulation of Mechanical Corrosion of Cement Composites Using Abrasive Water Flow. Acta Polytechnica CTU Proceedings, 22, 31–37. https://doi.org/10.14311/APP.2019.22.0031

[15] Srivastava, A. K., Nag, A., Dixit, A. R., Tiwari, S., & Srivastava, V. S. (2019). Parametric Study During Abrasive Water Jet Turning of Hybrid Metal Matrix Composite. In S. Hloch, D. Klichová, G. M. Krolczyk, S. Chattopadhyaya, & L. Ruppenthalová (Eds.), Advances in Manufacturing Engineering and Materials (pp. 72–84). Springer International Publishing. https://doi.org/10.1007/978-3-319-99353-9_9

[16] Szatkiewicz, T., Perec, A., Radomska-Zalas, A., Banaszek, K., & Balasz, B. (2023). Preliminary Studies into Cutting of a Novel Two Component 3D-Printed Stainless Steel–Polymer Composite Material by Abrasive Water Jet. Materials, 16(3), 1170. https://doi.org/10.3390/ma16031170

[17] Hloch, S., Hlaváček, P., Vasilko, K., Cárach, J., Samardžić, I., Kozak, D., Hlavatý, I., Scucka, J., Klich, J., & Klichova, D. (2014). Abrasive waterjet (AWJ) titanium tangential turning evaluation. Metalurgija -Sisak Then Zagreb-, 53, 537–540.

[18] Uthayakumar, M., Khan, M. A., Kumaran, S. T., Slota, A., & Zajac, J. (2016). Machinability of Nickel-Based Superalloy by Abrasive Water Jet Machining. Materials and Manufacturing Processes, 31(13), 1733–1739. https://doi.org/10.1080/10426914.2015.1103859

[19] Yuvaraj, N., & Pradeep Kumar, M. (2015). Multiresponse Optimization of Abrasive Water Jet Cutting Process Parameters Using TOPSIS Approach. Materials and Manufacturing Processes, 30(7), 882–889. https://doi.org/10.1080/10426914.2014.994763

[20] Khan, A., & Maity, K. P. (2016). Application of MCDM-Based TOPSIS Method for the Optimization of Multi Quality Characteristics of Modern Manufacturing Processes. International Journal of Engineering Research in Africa, 23, 33–51. https://doi.org/10.4028/www.scientific.net/JERA.23.33

[21] Venkateshwar Reddy, P., Suresh Kumar, G., & Satish Kumar, V. (2020). Multi-response Optimization in Machining Inconel-625 by Abrasive Water Jet Machining Process Using WASPAS and MOORA. Arabian Journal for Science and Engineering, 45(11), 9843–9857. https://doi.org/10.1007/s13369-020-04959-9

[22] Hloch, S., Srivastava, M., Krolczyk, J. B., Chattopadhyaya, S., Lehocka, D., Simkulet, V., & Krolczyk, G. M. (2018). Strengthening Effect after Disintegration of Stainless Steel Using Pulsating Water Jet. In Tehnicki Vjesnik-Technical Gazette (Vol. 25, Issue 4, pp. 1075–1079). UNIV OSIJEK, TECH FAC. https://doi.org/10.17559/TV-20170327134630

[23] GMA Garnet Group. (2020). Our Garnet for Future Generations. https://www.gmagarnet.com/en-us/recycling

[24] Martin, G. R., Lauand, C. T., Hennies, W. T., & Ciccu, R. (2000). Abrasives in water jet cutting systems (G. N. Panagiotou & T. N. Michalakopoulos, Eds.). Balkema Publishers.

[25] Jinhong Mining Catalog of Products. (2019, October 10). Lianyungang Jinhong Mining Co. Ltd. http://www.lygjhky.com/Hva_En/Catalog.pdf

[26] Taherdoost, H. (2023). Analysis of Simple Additive Weighting Method (SAW) as a MultiAttribute Decision-Making Technique: A Step-by-Step Guide. Journal of Management Science & Engineering Research, 6(1), 21–24. https://doi.org/10.30564/jmser.v6i1.5400

[27] Perec, A., & Radomska-Zalas, A. (2022). WASPAS Optimization in Advanced Manufacturing. Procedia Computer Science, 207, 1193–1200. https://doi.org/10.1016/j.procs.2022.09.175

[28] Keshavarz-Ghorabaee, M., Amiri, M., Zavadskas, E. K., Turskis, Z., & Antucheviciene, J. (2021). Determination of Objective Weights Using a New Method Based on the Removal Effects of Criteria (MEREC). Symmetry, 13(4), 525. https://doi.org/10.3390/sym13040525