

EVALUATION OF MACHINABILITY BASED ON CUTTING FORCE AND SURFACE QUALITY CHARACTERISTICS USING THE TOPSIS METHOD

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Abstract. *The study proposes a multi-criteria machinability evaluation based on cutting forces, surface quality, and productivity characteristics obtained from CNC milling experiments. Three tool steels (1.2379, 1.2842, and ES Aktuell 1200) and four long-reach milling cutters were tested under controlled machining conditions. The experimental data set, including force components and surface roughness parameters, was analysed using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method to integrate multiple performance indicators into a single metric, referred to as the Cutting Ability Index (CAI). The results show that the proposed approach enables the ranking of material-tool combinations and provides a more comprehensive interpretation of machinability compared to single-parameter evaluations. However, the resulting rankings are sensitive to the selection and balance of input criteria and, in certain cases, deviate from expected physical behaviour. This highlights the limitations of equally weighted multi-criteria approaches and underscores the importance of appropriate parameter selection and weighting. The study confirms that while TOPSIS can serve as an effective decision-support tool in machining analysis, its application requires careful methodological consideration.*

Keywords: *machinability; CNC milling; TOPSIS; multi-criteria decision making; surface roughness.*

1. Introduction

In machining technology, process parameters and circumstances such as cutting speed, feed rate, and depth of cut, tool and material properties also significantly influence surface quality, tool wear, energy consumption, and productivity. However, these performance measures often conflict with each other. Therefore, parameter selection cannot be treated as a single-objective optimization problem [1].

Traditional optimization approaches typically focus on a single objective function, which cannot adequately handle the multivariate and complex nature of machining processes. As a result, increasing attention is being paid to Multi-Criteria Decision Making (MCDM) methods, which enable the simultaneous consideration of multiple conflicting criteria [2].

In machining applications, performance evaluation often requires the joint

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consideration of quality, economy, and process stability. Such problems can be addressed using MCDM methods, which provide a structured and mathematically based ranking of alternatives by evaluating multiple criteria simultaneously [3]. MCDM approaches typically rely on a decision matrix, followed by normalization, weighting, and aggregation steps. Several methods have been developed, including AHP, ELECTRE, VIKOR, and TOPSIS, all aiming to compare alternatives across multiple, often conflicting criteria [4].

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was introduced by Hwang and Yoon as a multi-attribute decision-making method based on the principle that the optimal alternative has the shortest distance from the ideal solution and the greatest distance from the anti-ideal solution [5]. The method is particularly suitable for processing engineering and experimental data due to its simple mathematical structure and clear ranking procedure.

The application of TOPSIS has been reported in machining research. Previous studies have investigated the multi-criteria optimization of CNC turning parameters, where surface roughness and material removal rate were evaluated simultaneously [6]. Other studies have combined TOPSIS with statistical and optimization techniques to achieve a more comprehensive evaluation of machining responses [7].

The aim of this study is to develop a multi-criteria framework for assessment of machinability, integrating cutting force and surface quality into a unified performance indicator. The approach enables the interpretation of machinability as a composite, data-driven property. The TOPSIS method is applied to construct a Cutting Ability Index (CAI), supporting the ranking of technological alternatives. The aim of this article is to examine the applicability and sensitivity of the method. The novelty of this study lies in modelling machinability as a unified and interpretable performance measure.

2. Material and methods

The study is based on an end-milling experiment, which varies the cutting parameters, tool geometries and workpiece materials. The test ensures different types of comparisons. The cutting experiments were performed on a Mazak Nexus 410A-II CNC machining centre. During the experiments, long-reach milling tools were used, which represent particularly critical, vibration-sensitive machining conditions in manufacturing technology. The experiments were designed to evaluate different material–tool–parameter combinations under identical machining conditions, considering multiple performance criteria simultaneously.

Four different long-reach milling tool types (F1–F4) were used for the test, which differed in the number of teeth, edge geometry and tool rake angle. Figure 1 shows the main tool characteristics. Every tool contains partially polished blade for cutting corner reinforcement. The F1 and F3 tools have special protective chamfer, which allows higher feed; and they have variable helix angle, which ensures higher

material removal rate and tool life by minimizing the vibration and oscillation. The F3 and F4 tools contain special edge conditioning, which increases the edge stability and tool life. The F2, F3 and F4 tools contain chip breakers, which are advantageous for large depth of cut. Finally the F2 tool has variable tool pitch to reduce vibration and noise, and ensures better surface quality; further, the increased core diameter improves the tool rigidity.

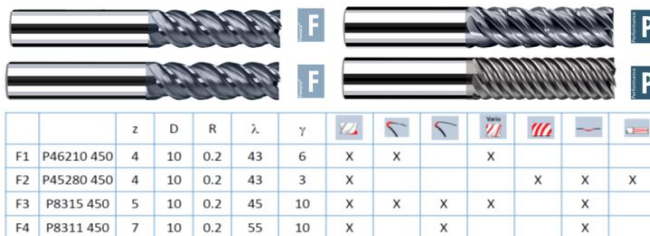


Figure 1 - Applied tools and their properties.

The tests were carried out on three alloyed tool steel grades: 1.2842 (90MnCrV8), 1.2379 (X153CrMoV12), and ES Aktuell 1200. Their tensile strength (R_m) and chemical compositions are summarized in Table 1.

Table 1. - Chemical composition and mechanical properties of the investigated materials.

Material	R_m [MPa]	C%	Cr%	Mn%	Mo%	Ni%	Si%	V%
1.2842	1050	0.90	0.35	2.00	-	-	0.25	0.10
1.2379	1000	1.55	11.30	0.30	0.75	-	0.30	0.75
ES1200	1200	0.26	1.25	-	0.50	1.05	0.10	0.10

The materials differ significantly in carbon and alloying element content, resulting in distinct mechanical and machining properties. Steel 1.2842 provides a balanced combination of hardness and machinability. In contrast, 1.2379, with its high carbon and chromium content, exhibits high hardness and wear resistance but reduced machinability. The ES Aktuell 1200 is a non-standard grade. It has a lower carbon content and a more complex alloying system, leading to improved toughness and different cutting characteristics, particularly under dynamic loading conditions.

The cutting speed was constant ($v_c = 50$ m/min, $n = 1590$ 1/min) throughout the entire series of experiments, in order to ensure that the effects examined were primarily due to changes in the feed parameters, tool geometry and material properties. The feed per tooth (f_z) was varied at four levels: 0.03; 0.05; 0.07 and 0.09 mm. The axial depth of cut was fixed at $a_p = 35$ mm throughout the entire series of experiments, while the radial depth of cut was fixed at $a_e = 0.2$ mm. Table 2 shows

the cutting parameters. The feed rate (v_f) is determined by feed per tooth (f_z), spindle speed (n) and number of teeth (z). The feed rates (v_f) for the different tool and feed combinations were determined based on the number of teeth and the feed per tooth. These values are detailed in Table 2.

Based on the cutting parameters the material removal rate (MRR , mm^3/min) was calculated, as the indicator of the productivity.

$$MRR = V_f \cdot a_e \cdot a_p \tag{1}$$

Table 2. - Cutting parameters.

Tool	f_z [mm/tooth]	v_f [mm/min]	v_c [m/min]
F1	0.03	190.8	50
	0.05	318.0	
	0.07	445.2	
	0.09	572.4	
F2	0.03	190.8	
	0.05	318.0	
	0.07	445.2	
	0.09	572.4	
F3	0.03	238.5	
	0.05	397.5	
	0.07	556.5	
	0.09	715.5	
F4	0.03	333.9	
	0.05	556.5	
	0.07	779.1	
	0.09	1001.7	

The cutting performance was characterised by cutting force components and surface roughness parameters. The cutting force components were measured by a Kistler 9257B piezoelectric dynamometer during the cutting process. The measuring system recorded the three orthogonal cutting force components, namely the axial force (F_z), the feed force (F_f) and the passive force (F_p). The force data were evaluated using the Kistler DynoWare software, which enabled the processing of time-dependent force signals and the determination of statistical characteristics.

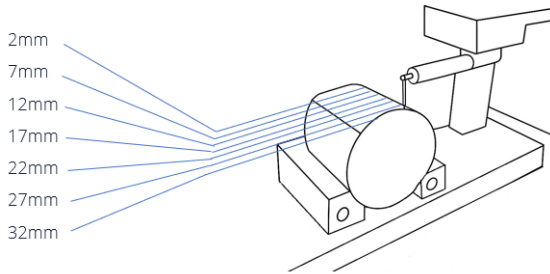


Figure 2 - Surface roughness measurement.

To characterize the quality of the machined surfaces, surface roughness measurements were performed by a Mahr-Perthen GD120 roughness measuring device. For each parameter setting, the roughness parameters were measured at seven different positions on the machined surface (Figure 2). During the roughness evaluation, the parameters R_a , R_z and R_{Sm} were examined, and the mean value and the standard deviation were calculated in each case.

The cutting force components, surface roughness characteristics and material removal rate together formed an extensive database, which served as the basis for the subsequent multi-criteria decision support analysis. Using the collected data, the different material-tool-technology alternatives were objectively compared and ranked using the TOPSIS method.

3. Multi-criteria decision and the TOPSIS method

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method used in this research is one of the best-known and most widely used MCDM methods. The basic idea of the method is that the optimal alternative is the one that is as close as possible to the ideal solution, while being the farthest from the anti-ideal solution. The ideal solution is a theoretical reference state that contains the most favourable values for each criterion, while the anti-ideal solution consists of the most unfavourable values [8].

The first step in applying the TOPSIS method is to establish a decision matrix that contains the criterion values for the alternatives:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (2)$$

Due to the different units of measurement, the elements of the decision matrix cannot be directly compared, so normalization is necessary. The most common method used in TOPSIS is vector normalization, which can be described by the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (3)$$

The elements of the normalized decision matrix were then multiplied by weight factors expressing the relative importance of the criteria, resulting in the weighted normalized decision matrix. In the present study, all criteria in the decision matrix were assigned the same weight values, i. e. each characteristic contributed equally to the evaluation of the alternatives. This approach was used to avoid prior preference for a single cutting characteristic and to ensure a balanced consideration of cutting force and surface quality parameters. The weighting thus created does not result in an absolute machinability index, but expresses a compromise performance interpreted based on the criteria involved.

Based on these, the so-called ideal and anti-ideal solutions can be determined. The ideal solution represents a theoretical reference state that contains the most favourable values possible for the criteria under study, while the anti-ideal solution is built up of the most unfavourable values. Based on the nature of the criteria, the ideal solution is determined by selecting the maximum values for benefit-type criteria, while the minimum values for cost-type criteria; the anti-ideal solution accordingly contains the opposite extreme values.

Subsequently, the distance from the ideal and anti-ideal solutions is determined for each alternative examined. These distances express the extent to which the given alternative approaches the optimal state and how far it is from the most unfavourable solution. This step of the method allows for an objective comparison of alternatives in the multidimensional criterion space and establishes the basis for the subsequent ranking, which takes into account the proximity to the good solution and the distance from the bad solution together (Figure 3).

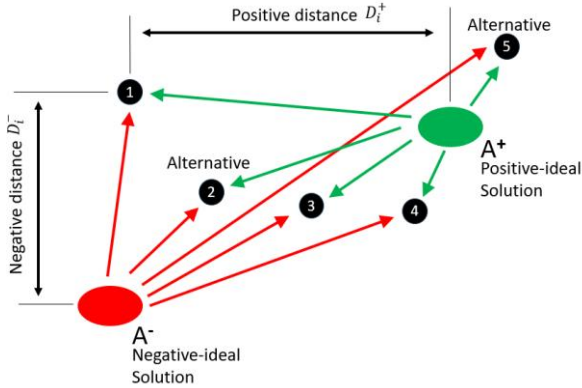


Figure 3 - Interpretation of the distance measured from each alternative in the TOPSIS system.

During the ranking, the evaluation of each alternative is done by taking into account the distances measured from the ideal and anti-ideal solutions together. To quantify this, the TOPSIS method uses the relative proximity coefficient, which expresses how close the given alternative is to the ideal solution compared to the most unfavorable state. The basis for the final ranking is the relative proximity coefficient:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (4)$$

The value of C_i ranges between 0 and 1; the higher its value, the more favorable the given alternative is, since it is closer to the ideal solution and further away from the anti-ideal state. The advantage of the TOPSIS method is that it has a simple and understandable mathematical structure, provides a complete ranking of alternatives, and can be effectively applied to multi-criteria evaluation of engineering experimental data, especially when the examined criteria can be measured numerically [5][9].

4. Results and Discussion

Because of the interdependence of the evaluated parameters, the results and their interpretation are presented together in this section.

Table 3 summarises the type of parameters used in the TOPSIS analysis and their roles. The selected variables represent the key aspects of machining performance, including cutting forces, surface quality, and productivity. Only the most representative parameters were considered in order to ensure a balanced and transparent evaluation while avoiding redundancy in the dataset.

Table 3. - Criteria used in the TOPSIS analysis

Parameter	Description	Role in analysis	Type
F_i	Radial cutting force	Load	Cost
R_i	Surface roughness	Surface quality	Cost
MRR	Material removal rate	Productivity	Benefit

Cutting force and surface roughness parameters were treated as cost-type criteria (lower values are preferable), while material removal rate was considered a benefit-type criterion. During the analyses the following parameters were considered: F_{f_mean} , F_{f_max} , F_{p_mean} , F_{p_max} , F_{z_mean} , F_{z_max} , R_{a_mean} , R_{a_SD} , R_{z_mean} , R_{z_SD} , $R_{Sm/fz}$, R_{Sm_SD} and MRR (SD means standard deviation).

The presentation of all data is not possible because of the amount and variation of measured parameters, but some examples are presented in order to demonstrate the problem of the assessment. Figure 4 shows the measured surface roughness (R_a) and axial cutting force (F_z) data as a function of material grade. The mean value of R_a is the smallest in case of ES1200, but the mean of F_z is the largest.

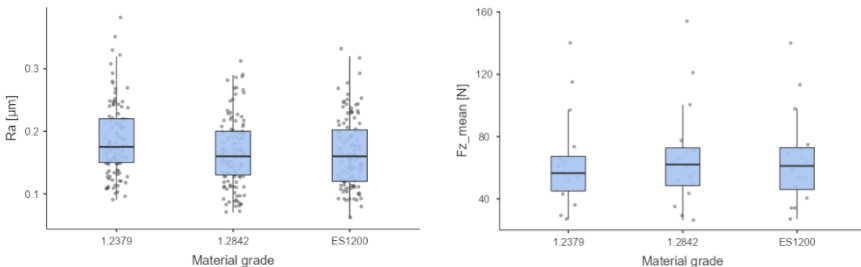


Figure 4. Distribution of surface roughness (R_a) and axial cutting force (F_z) values for different material grades.

Figure 5 shows the measured surface roughness (R_a) and axial cutting force (F_z) values as a function of cutting tool. The results indicate that the applied tool geometry has a noticeable influence on both surface quality and cutting forces. Tool F2 performs the highest R_a values and the greatest variation, while tool F4 results in lower R_a values with reduced variability. In contrast, the axial cutting force shows an increasing trend from F1 to F4, with tool F4 producing the highest force levels, because of the 7 teeth.

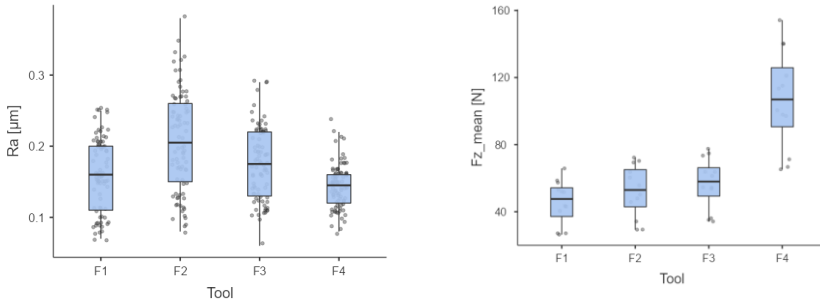


Figure 5. Distribution of surface roughness (R_a) and axial cutting force (F_z) values for different cutting tools.

Figure 6 presents box plots of the average passive cutting force (F_{p_mean}) values as a function of both material grade and cutting tool. The results indicate that ES1200 exhibits the highest average passive force, while materials 1.2379 and 1.2842 show lower and comparable values. A clear increasing trend can also be observed across the cutting tools, with tool F4 producing the highest and tool F1 the lowest force levels, while tools F2 and F3 form an intermediate group.

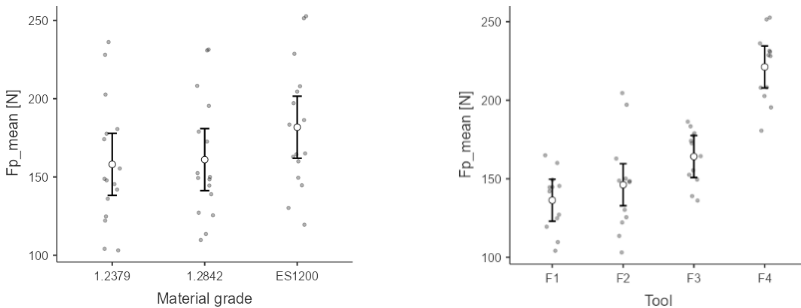


Figure 6 - Average passive cutting force (F_{p_mean}) values for different material grades and cutting tools.

The elevated force levels observed for tool F4 may be attributed to its higher number of cutting edges ($z = 7$). Under identical feed conditions, a larger number of teeth are engaged simultaneously in the cutting process, which can increase the contact area and, consequently, the passive cutting force. In addition, reduced flute space may hinder chip evacuation, further contributing to higher force levels.

The difference between tools F1 and F2, despite having the same number of teeth, may be related to their different rake angles. Tool F1, with a higher rake angle ($\gamma = 6^\circ$), promotes more favourable chip formation, resulting in lower cutting forces, whereas the lower rake angle of tool F2 ($\gamma = 3^\circ$) may increase cutting resistance.

Figure 7 shows the material removal rate (*MRR*) values as a function of cutting tool. The results indicate a clear increasing trend from tool F1 to F4, with tool F4 achieving the highest *MRR* values, while tool F1 presents the lowest productivity. This trend is directly related to the number of cutting edges, as a higher tooth count increases the feed rate under identical feed per tooth conditions, resulting in a higher material removal rate.

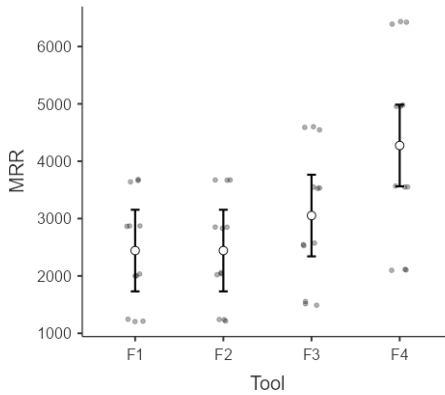


Figure 7. Material removal rate (*MRR*) values for different cutting tools

The larger deviation observed for tool F4 may be attributed to the wider range of applicable cutting conditions, as well as increased sensitivity to process parameters such as feed rate. In addition, the higher number of engaged cutting edges may lead to more complex chip formation and evacuation conditions, which can contribute to increased variability in the calculated *MRR* values.

The presented particular parameters cannot be used to evaluate the performance of the cutting tools, or machinability of the materials. Therefore, an overall assessment is required. Now the application of the TOPSIS method is presented.

The TOPSIS method enables the reduction of a large set of measured data into a single performance indicator, allowing the ranking of materials, tools, and process parameters. In this study, a Cutting Ability Index (CAI) was introduced to quantify machinability by integrating multiple performance criteria into a unified metric.

Figure 8 presents the TOPSIS-based ranking of the investigated materials and cutting tools expressed by the CAI values. Among the materials, 1.2379 achieved the highest relative proximity coefficient ($C_i = 0.75$), followed by 1.2842 ($C_i = 0.48$), while ES1200 exhibited the lowest value ($C_i = 0.31$). According to the CAI, material 1.2379 shows the most favourable overall machinability under the investigated conditions. This result is somewhat unexpected, considering that its higher alloying

content and mechanical strength are generally associated with less favourable machinability. However, the CAI reflects the combined effect of cutting forces, surface quality, and productivity, indicating a more balanced overall performance.

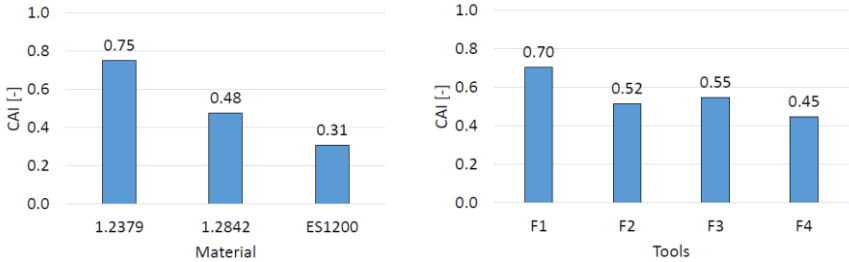


Figure 8. TOPSIS-based ranking of the investigated materials and cutting tools expressed by the Cutting Ability Index (CAI).

For the cutting tools, tool F1 achieved the highest ranking ($C_i = 0.70$), followed by F3 ($C_i = 0.55$) and F2 ($C_i = 0.52$), while tool F4 exhibited the lowest value ($C_i = 0.45$). This result highlights that the best overall performance is not determined by a single parameter, but by the balance between competing criteria. Although certain tools may provide advantages in specific aspects, the CAI identifies tool F1 as the most favourable option due to its balanced machining performance.

Figure 9 presents the TOPSIS-based ranking of the investigated cutting tools for each material separately. The results show that tool F1 consistently achieves the highest CAI values across all materials, while tool F4 generally exhibits the lowest performance.

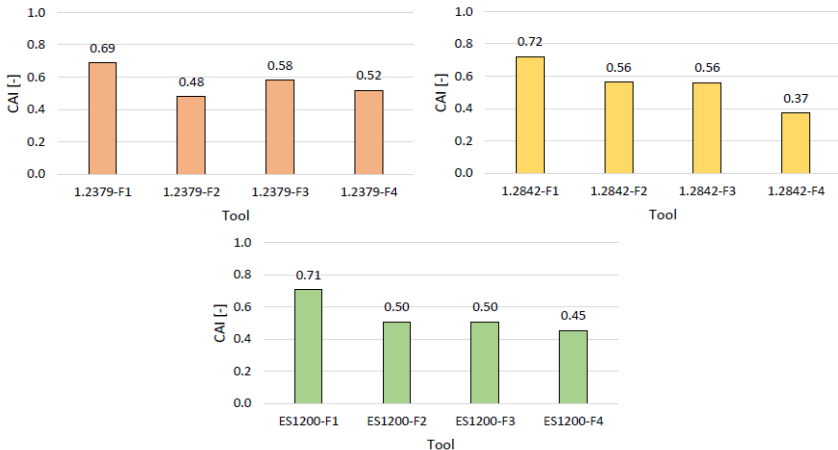


Figure 9. TOPSIS-based ranking of cutting tools for each material using the Cutting Ability Index (CAI).

These results highlight that the performance of cutting tools is strongly dependent on the material–tool combination, and that different evaluation perspectives can reveal additional relationships within the dataset. While global rankings provide an overall comparison, the material-specific analysis allows a more detailed interpretation of machining performance.

Figure 10 presents the TOPSIS-based ranking of the investigated materials for each cutting tool. The results indicate that the relative performance of the materials varies depending on the applied tool, confirming that machinability cannot be described independently of the tool geometry. While material 1.2842 achieves the highest CAI values for tools F1, F2, and F3, tool F4 shows a different trend, where ES1200 exhibits the most favourable performance.

This variation highlights the interaction between tool geometry and material properties, suggesting that the optimal material–tool combination depends on the specific cutting conditions. The results further demonstrate that the proposed CAI-based approach enables multi-perspective evaluation, providing deeper insight into machining behaviour beyond conventional single-factor analyses.

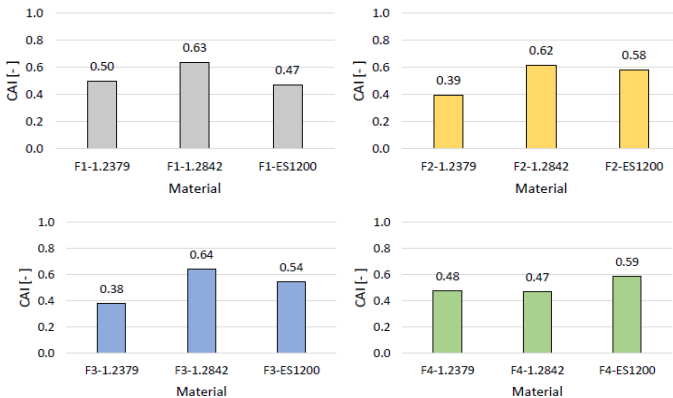


Figure 10. TOPSIS-based ranking of materials for each cutting tool using the Cutting Ability Index (CAI).

5. Summary

This study presented a multi-criteria evaluation for machinability based on cutting force, surface quality, and productivity characteristics, using the TOPSIS method. The proposed approach integrates multiple, often conflicting performance

indicators into a single comparative index, defined as the Cutting Ability Index (CAI), enabling the ranking of materials and cutting tools under identical machining conditions.

The results confirmed that machinability strongly depends on the material–tool combination. However, the obtained rankings revealed several inconsistencies with expected physical behaviour. Material 1.2379 achieved the highest CAI value despite its unfavourable composition and mechanical properties, while tool F4, although providing the highest material removal rate, exhibited one of the lowest overall rankings. These findings clearly demonstrate that the results are highly sensitive to the selection and interaction of input parameters.

This observation highlights a fundamental limitation of the TOPSIS-based approach: the resulting ranking does not necessarily represent the actual machinability behaviour. Favourable values in certain criteria (e.g., cutting force or surface quality) may not compensate for disadvantages in others (e.g., productivity), which may lead to misleading conclusions. The inconsistencies observed do not indicate limitations of the TOPSIS method itself, but rather reflect the sensitivity of multi-criteria evaluation to the definition of input parameters.

Therefore, the appropriate selection, weighting and number of input parameters are critical for obtaining reliable results. The selected parameter set in this study does not fully capture the complexity of the machining process. Additional factors such as tool wear, vibration, temperature, or energy consumption may also significantly influence machinability and should be considered in future studies. Furthermore, the applied cutting conditions, particularly the cutting speed, may alter the relative performance of the tools, indicating that different parameter ranges could lead to different rankings.

The proposed CAI represents a step toward a data-driven and quantitative characterization of machinability as a measurable and comparable property. However, its effectiveness strongly depends on the appropriate definition of the evaluation model; therefore, it should be interpreted as part of a broader analytical framework rather than as a standalone indicator.

Overall, the study demonstrates that while TOPSIS provides an effective framework for integrating multiple machinability-related criteria into a single performance index, the validity of the resulting rankings critically depends on careful model definition. When appropriately applied, the method can support advanced, data-driven approaches for machining process evaluation and optimization.

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ОЦІНКА ОБРОБЛЮВАНОСТІ МАТЕРІАЛУ ВИРОБУ НА ОСНОВІ СИЛИ РІЗАННЯ ТА ХАРАКТЕРИСТИК ЯКОСТІ ПОВЕРХНІ З ВИКОРИСТАННЯМ МЕТОДУ TOPSIS.

Анотація. Дослідження пропонує багатокритерійну оцінку обробності на основі сил різання, якості поверхні та продуктивних характеристик, отриманих у експериментах з фрезеруванням на верстаті з ЧПУ. Три інструментальні сталі (1.2379, 1.2842 та ES Aktuell 1200) та чотири циліндричні фрези збільшеної довжини тестувалися в умовах контрольованої обробки. Експериментальний набір даних, включно з компонентами сили та параметрами шорсткості поверхні, був проаналізований за методом TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) для інтеграції кількох показників ефективності в одну метрику, відому як Індекс Cutting Ability (CAI). Результати показують, що запропонований підхід дозволяє ранжувати комбінації матеріалів і інструментів і забезпечує більш комплексне тлумачення обробності порівняно з однопараметричними оцінками. Однак отримані рейтинги чутливі до вибору та балансу критеріїв вхідних даних і в певних випадках відхиляються від очікуваної фізичної поведінки. Тому відповідний вибір, зважування та кількість вхідних параметрів є критично важливими для отримання надійних результатів. Вибраний набір параметрів у цьому дослідженні не повністю відображає складність процесу обробки. Додаткові фактори, такі як знос інструменту, вібрації, температура або енергоспоживання, також можуть суттєво впливати на оброблюваність і слід враховувати в майбутніх дослідженнях. Крім того, прикладені умови різання, особливо швидкість різання, можуть впливати на відносну продуктивність інструментів, що свідчить про те, що різні діапазони параметрів можуть призводити до різних рівнів. Це підкреслює обмеження рівноважних багатокритерійних підходів і підкреслює важливість відповідного вибору та зважування параметрів. Дослідження підтверджує, що хоча TOPSIS може слугувати ефективним інструментом підтримки прийняття рішень у аналізі машинної обробки, його застосування потребує ретельного методологічного розгляду.

Ключові слова: оброблюваність; фрезерування з ЧПУ; TOPSIS; багатокритеріальне прийняття рішень; поверхнева шорсткість.