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Research Article

Experimental investigation and optimization of turning parameter for enhanced machinability of titanium alloy Ti410A

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ABSTRACT

The study deals with the optimization of turning parameters for Titanium Alloys Ti410A, which is an important parameter for aerospace, biomedical and industrial applications due to its better machinability results. Ti410A is difficult to machine because of its low thermal conductivity and high chemical reactivity resulting in excessive tool wear and poor surface finish. The purpose of the research is to systematically investigate the effect of cutting speed, feed rate and depth of cut on MRR, surface roughness and tool wear in dry turning. The Taguchi L16 orthogonal array was used in a structured experimental approach and ANOVA was used for statistical analysis. Also, to identify the optimal machining variables, MADM techniques, i.e., MOORA and TOPSIS were combined with entropy-based weighting. The results revealed that the surface roughness and tool wear were significantly affected by cutting speed and the effect of feed rate on MRR was significant. The best machining parameters found were cutting speed of 557 m/min, feed rate of 0.167 mm/rev and depth of cut of 0.4 mm which produced a high MRR of 74.42 mm^3/min, a low surface roughness of 0.90 µm and a low tool wear of 0.2892 mm. This study has the novelty of combining the MOORA and TOPSIS method with entropy-based weighting for optimization of Ti410A machining, which is not detailed in the previous studies. The methodology is applicable for making cost effective data driven approach to improve machining performance and will be helpful for industrial application.

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INTRODUCTION

The exceptional properties of titanium and its alloys, such as their high ratio of strength to weight, very good corrosion resistance and excellent biocompatibility, make them widely used in various industries, including the aerospace, biomedical, automotive and marine industries.

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However, these desirable properties make it difficult to machine titanium alloys [1]. Due to the low thermal conductivity and high chemical reactivity of titanium alloys, rapid tool wear, high cutting forces and difficulty in achieving desired surface finish are contributed. Ti410A has received much interest because of its compromise of mechanical characteristics and machinability. Therefore, it is vital to optimize the cutting parameters to achieve better machinability of Ti410A, which would improve the efficiency, reduce machining costs and prolong tool life [2].

Titanium alloys are used in a broad range of applications and are commonly formed into desired parts by the turning process. The following cutting parameters have a significant influence on the efficiency of the turning operation: cutting speed, feed and depth of cut, tool geometry. If these parameters are not selected properly, poor surface finish, excessive tool wear and lower material removal rates occur. So, experimental study of turning parameters coupled with an optimization approach would be necessary to have better machinability and performance [3,4]. Surface roughness, tool wear, cutting force, and chip morphology are all indicators used for assessing the machinability of titanium alloys including Ti410A. Surface roughness is one of the important quality characteristics of the produced workpieces and is a quality factor for their functionality especially in high precision applications. Tool wear has a direct impact on the production cost and tool life, so it is an important parameter of the optimization of machine tool production process [5]. Furthermore, cutting forces are important in the evaluation of the stability of the machining process and can affect the deflection of tools and integrity of the part. The study on the morphology of the chips can provide information on the mechanism of material removal and help to determine the optimum cutting conditions [6]. Various optimization techniques have been used to improve the machinability of titanium alloys. The traditional trial-and-error approach is time-consuming and inefficient and is not well suited for modern manufacturing environments. As compared to it, statistical/computational optimization methods like Taguchi method, RSM, GA, and ANN are systematic and efficient methods for parameter optimization. One of the most widely used techniques is RSM, which has proved to be successful in modeling the complex relationships between the machining parameters and the performance measures with a minimum number of experimental runs [7-9].

Gupta et al. [10] optimized the machining parameters for Titanium-II alloy using RSM and PSO under MQL. Lower cutting speed was found to be more beneficial in terms of minimizing tool wear, surface roughness, and tangential cutting force. PSO yielded results which are in closer agreement with experimental values as compared to desirability approach. The results showed that the machining properties and chip shapes were better in MQL than in dry conditions. Dandekar et al. [11] investigated the process of LAM and hybrid of Ti–6Al–4V to improve its machinability. Hybrid machining extended tool life by 2 times and LAM increased tool life by 1.7 times at 107 m/min. The best material removal temperature was 250°C and the tools coated with TiAlN gave a 2-3 times improvement. Economic analysis showed that cost savings are ~30% for LAM and ~40% for hybrid machining processing, and the material removal rate is increased by 80%. Ravikumar et al. [12] studied Al7075/SiC/Al_2O_3 hybrid composites with addition of 2–8 wt. % of SiC and Al_2O_3. The heat treatment at 480°C/Water and Ice quenching increased tensile strength, hardness and wear resistance. Samples that were ice quenched had the highest strength. Higher ceramic content resulted in greater wear resistance. The structural integrity was verified by SEM and EDS analyses.

Suchendra et al. [13] investigated Al6061– Al_2O_3–MoS_2 hybrid composites that were fabricated using the stir casting method. The heat-treatment of 510°C followed by quenching in ice resulted in hardness improvement to 138.1 VHN and also increased the tensile and the wear resistance of the material. Microstructural analysis showed a good dispersion of reinforcement. The fracture surfaces showed voids and dimples and worn-out surfaces showed delamination. Samples that had been ice quenched showed superior mechanical properties and wear. Madgule et al. [14] produced aluminium foam using powder metallurgy method with adding wax powder as foaming agents. The effect of particle size, mixing speed, temperature and foaming agent concentration on mechanical properties was studied. Properties were greatly affected by powder size. The highest value of porosity obtained was 71.30% while the compression; tensile and flexural strength values were 12.01 MPa, 6.16 MPa and 5.18 MPa respectively. ANOVA analysis was used to identify the key parameters. No significant variations in composition were found by microstructure analysis. Wax powder was used as new foaming agent in the study, which led to better properties. Sahu and Andhare [15] investigated the optimization of machining parameters for turning Ti-6Al-4V using RSM and advanced optimization algorithms (TLBO, 'JAYA', and GA). Results demonstrated TLBO and 'JAYA' excelled GA in diminishing roughness of surface and cutting force. Optimal cutting speed (171.4 m/min) and lower feed rate (55.6 mm/min) enhanced machinability.

Outeiro et al. [16] analysed the machining of Ti-6Al-4V titanium alloy using ML and DOE methods. Various tool geometry and cutting parameters were used for orthogonal cutting tests. Surface integrity was improved by increasing the rake angle (from 6° to 5°) and edge radius (from 16 μm to 30 μm), which caused the residual stresses to be reduced by 40%.Selvakumar et al. [17] optimized Micro-turning parameters for Titanium alloy by RSM and BBD. To minimize tool wear, the cutting speed of 3459 rpm was used; feed rate of 7.4 μm/rev, and depth of cut 15 μm, which yielded 100% desirability. ANOVA confirmed the significance of parameters, which improves the machinability and tool life. Kechagias et al. [18] compared the TED and FFD for the prediction of machinability in the turning of

Ti-6Al-4V ELI alloy. The cutting force and surface roughness were examined. The differences in cutting force and surface roughness among the depths of cut were significant, as revealed by ANOVA, and feed rate influenced the surface roughness. With the optimized parameters (850 rpm spindle speed, 0.1 mm/rev feed rate and 0.5 mm depth of cut), the lowest cutting force (132 N) and best surface roughness (1.27 μm) was obtained, which proves that the TED could be used in the machining studies. Sahoo et al. [19] have investigated the machinability of titanium diamond by electroporation spark machining. The parameters, such as peak current (9A) and pulse-on time (1010 μs), were optimized using a FFD procedure which determined that the MRR (7.753 mg/min) was the highest while the tool wear rate (0.020 mg/min) and surface roughness (5.46 μm) were the lowest. D'Mello et al. [20] optimized the parameters of high-speed turning of Ti-6Al-4V using swarm intelligence techniques: FA, PSO and BA. BA achieved the lowest surface roughness (Ra = 0.6300 μm, Rt = 2.6613 μm) at 199.51 m/min cutting speed, 0.156 mm/rev feed, and 0.998 mm depth of cut. The laser engraving process for Ti–6Al–4V alloy with 50W fiber laser was investigated by Kasman et al. [21]. The optimum parameters are scan speed (100 mm/s), scan direction (90°/0°), and fill spacing (0.02 mm), which resulted in the minimum surface roughness (9.81 μm) and the maximum engraving depth (248 μm). The surface roughness (53 %) and engraving depth (64 %) were confirmed to be influenced by scan speed by ANOVA.

Yang et al. [22] developed a new MADM method called ICEI-MADM to choose the most appropriate titanium alloy material for biomedical applications. It used the preference weighted averages of CEIs for 22 Ti alloys. The highest of these was Ti-12Mo-6Zr-2Fe (annealed); the next was Ti-15Mo-5Zr-3Al (aged); and the worst was Cp Ti. The alloys in the β-type group performed best, moderate for the α+β group, and the lowest for the α group. Sureja et al. [23] studied heat treatment processes using TOPSIS optimization technique. Under optimum conditions the experimental data indicated a hardness increase from 220 HV to 350 HV and an increase in tensile strength by 25%. The results showed that the optimization values obtained by TOPSIS were able to minimize the number of defects while improving durability, thereby demonstrating the effectiveness of the method in optimizing parameters for industrial applications. The implementation of various cutting tool materials, coatings and cooling techniques has been extensively studied in recent years to enhance the machining characteristics of Ti alloys. A number of carbide tools coated with the advanced coating (Titanium Aluminium Nitride (TiAlN) and Diamond-Like Carbon (DLC)) have been found to be effective in improving tool life and friction during the machining process [24-26]. Furthermore, it has been studied how MQL and cryogenic cooling technique can be applied to reduce heat generation and enhance surface finish [27-29]. Despite all these developments, however, more studies are needed to be performed to validate and optimize the process for Ti410A.

The interest in the optimisation of the machining process has been drawn to MADM techniques, particularly in relation to difficult materials like titanium alloys. In the selection of the best machining parameters to improve the machinability, various MADM methods have been assessed and the MOORA and the TOPSIS are found to be effective. The high strength-to-weight ratio, resistance to corrosion, and thermal stability make Ti-410A and other titanium alloys valuable materials for use in the aerospace, biomedical, and automotive industries. Despite their relatively high machining forces, high tool wear and poor surface integrity, these are not well machinable, however, and require the use of strong optimization techniques [30-31]. MOORA is one of the effective and simple MADM methods which considers more than one conflicting criteria to obtain the optimum set of machining parameters. The method allows to normalize the decision matrix and to calculate the ratio system; this helps to make a choice and, based on the performance indexes, to rank the options. When it comes to Ti alloy machining, MOORA can be used to optimize parameters like cutting speed, feed rate and depth of cut so as to maximize the surface roughness and minimize tool wear. The studies have shown that MOORA is very effective in finding the optimum combinations of the parameters that provide a better tool life and machining efficiency while maintaining product quality [32-33]. Likewise, TOPSIS has been widely applied to optimize the machinability as it evaluates best and worst solutions in the decision making process. TOPSIS calculates the Euclidean distance between each alternative and the ideal and anti-ideal solutions, and then ranks the alternatives according to the closeness coefficient. In selecting machining parameters for balancing surface roughness, MRR and cutting forces of Ti alloy machining, this method has been successfully applied. Researchers have discovered that the use of entropy weights with TOPSIS improves the effectiveness of the TOPSIS, and offers more objective criterion weighting mechanism, which yields more reliable and data-driven decisions [34-35]. MOORA and TOPSIS methods could be used as a systematic approach to deal with multiple machining criteria and provide a systematic way to improve the machinability of titanium alloys. Their quantitative and qualitative data processing capabilities enable them to be appropriate for manufacturing applications in the real world, enhancing efficiency, cost-effectiveness, and sustainability. Such use of the MADM techniques in the context of machining optimization allows them to inform the decision making process to enhance productivity while ensuring the desired quality of the machined titanium parts [36-37].

Although the optimization methods of different titanium alloys have been studied, there is still no systematic research on the optimal turning parameters of the Ti410A under dry cutting conditions. The attention in previous literature has been mainly given to conventional grades of titanium (e.g., Ti-6Al-4V) or to hybrid techniques of machining with cryogenic cooling and MQL. However, few studies have investigated the effect of cutting speed, feed rate and depth of cut on the tool wear, surface roughness and MRR using MADM methods, specifically MOORA and TOPSIS. The objective of this research is to conduct an experimental study with a systematic approach to optimize the turning conditions of Ti410A in order to overcome such gaps. The novelty of this work is based on its comprehensive analysis and enhancement of the machining parameters of Titanium Alloy Ti410A by an integrated approach using ANOVA, MOORA and TOPSIS methods. This study concentrates on Ti410A as opposed to the generic titanium alloys studied in previous research, as it poses some special challenges in terms of its machinability. The experiment is designed using a structured Taguchi design to determine the optimum machining parameters which can improve the material removal rate and reduce the surface roughness and tool wear. The incorporation of entropy-based MADM techniques further enhances the optimization process, leading to a comprehensive and data-driven selection of machining conditions. The lessons learned in this work help develop cost-effective and accurate machining approaches for Ti410A, providing guidelines for industrial applications in the aerospace, biomedical, and manufacturing industry.

This work builds on current Ti410A Titanium Alloy research and further studies the machinability of the alloy by performing a comprehensive experimental study that is then optimized using advanced optimization methods to improve machining performance. This research works systematically with several turning parameters by a comprehensive DOE approach rather than the previous studies which concentrated on individual turning parameters. Further, it uses optimization methods like RSM and multi-objective optimization for the optimal machining conditions, which improves the surface finish, tool life and MRR. The results provide a more practical and precise guideline for industry use, connecting theory and practice in machining.

Materials and Machining Parameters

Titanium Grade-2 round bars with a diameter of 50 mm and a length of 45 mm, underwent machining with a carbide insert bearing the ISO designation CNMG120408MS-PR1535, featuring chip-breaking geometry. The chemical composition of the material has been depicted in Table 1. The input machining parameters and their different levels as shown in Table 2 have been hereby selected as cutting speed, feed rate and depth of cut based on the literature. A proper layout for the experimentation has been required for the proper execution of the experimentation. So, this study utilised the Taguchi approach, and L_{16} orthogonal array has been utilized for conducting the experiments as illustrated in Table 3. The basis for using the Orthogonal Array L16 in the Taguchi Experimental Design is its ability to efficiently study multiple factors at different levels while minimizing the number of experiments. The L16 array is optimized for up to 15 independent variables at 4 levels each, suitable for optimizing parameters in turning operations. This design will maintain a balanced level of interaction between the factors and will minimize experimental time and cost, thus the reliability and robustness of the results will be increased. Finally, Dry turning of Titanium Grade-2 has been performed using a CNC Lathe Machine Vx-200 Mac Power, equipped with maximum spindle speed and power capabilities illustrated in Figure 1. The experiment was performed in advanced manufacturing process laboratory, institute of infrastructure, technology, research and management, Ahmedabad. The experimental design was carefully planned to carry out an optimum and systematic investigation of the turning parameters for Titanium Alloy Ti410A. The parameters for cutting speed, feed rate, the depth of cut and the nose radius were chosen as they had the most important effect on the aspects of the machinability such as surface roughness, tool wear and cutting forces. They were selected from an extensive literature review and preliminary trials to reflect a broad spectrum of practical machining conditions and are the key parameters in the study.

Table 1. Chemical substances available in titanium Grade-2

Element	**C max**	**Fe max**	**N max**	**H23 Max**	**O max**
Weight %	0.08 %	0.30 %	0.03 %	0.015 %	0.25 %

Table 2. Process variables with their level

Level	**Cutting speed (m/min)**	**Feed (mm/rev)**	**Depth of cut (mm)**
Level 1	247	0.067	0.2
Level 2	347	0.111	0.4
Level 3	557	0.133	0.6
Level 4	835	0.167	0.8

Table 3. The Taguchi DOE utilized an L16 orthogonal array

Experiment No.	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)
1	247	0.067	0.2
2	247	0.111	0.4
3	247	0.133	0.6
4	247	0.167	0.4
5	371	0.067	0.4
6	371	0.111	0.2
7	371	0.133	0.8
8	371	0.167	0.6
9	557	0.067	0.6
10	557	0.111	0.8
11	557	0.133	0.2
12	557	0.167	0.4
13	835	0.067	0.8
14	835	0.111	0.6
15	835	0.133	0.4
16	835	0.167	0.2

The superior mechanical properties of Ti410A, such as high strength, resistance to corrosion and versatility for aerospace and biomedical applications, were chosen. It is a useful material for optimization studies due to its machinability characteristics. The L16 orthogonal array was chosen as per Taguchi's robust design methodology that helps to minimise number of experiments and maximise efficiency of designs. This makes it possible to be comprehensive in analysing the machining parameters and achieve reliable and optimized results.

MEASUREMENT OF PERFORMANCE PARAMETERS

Surface Roughness after Dry Turning Process

The work piece which are dry turning on the CNC lathe machine VX200 are tested on Taylor-Hobson surface roughness tester for determination of surface roughness. The outcomes are obtained are illustrated in the Table 4. Following the experiment, a roughness testing device (Model: Surftest SJ-410, Make: Mitutoyo) was used to evaluate the machined surface roughness. 0.8 mm and 8 mm were chosen as for assessment and cut-off lengths, accordingly. As illustrated in Figure 2, an average of the four SR values was taken into account to guarantee consistency of the measuring apparatus.

Tool Wear after Dry Turning Process

The slow degradation of cutting tools brought on by frequent use is known as tool wear. As seen in Figure 3, tool wear was successfully assessed utilizing a Mitutoyo TM Series tool maker microscope. The results are obtained are tabulated in the Table 4.

Material Removal Rate

Quality of the dry turning process, the cutting process and cutting tool selection are measured by the material removal rate, or MRR. The amount of material removed in millimeters per minute (mm^3/min) during turning operations is known as the material removal rate, or MRR. The results are obtained are tabulated in the Table 4.

$$\text{Material removal rate (MRR) calculated} = \text{volume removed} \div \text{cutting time } (mm^3/min) \quad (1)$$

RESULTS AND DISCUSSION

Table 4 shows the chosen measurements of MRR, surface roughness, and tool wear based on Taguchi's L16OA. To get more precise readings for the study, all of the response measurements in Table 4 are averaged over three trials of the study. The detailed methodological investigation and testing of dry turning process is shown in Figure 4.

ANOVA Analysis for Response Measure

The relative effect of turning parameters on output metrics is clarified using the ANOVA approach. To assess the impact of turning variables on MRR as shown in Table 5, surface roughness as shown in Table 6, and tool wear as shown in Table 7, the p-value was calculated at a 95% confidence level. For any input variable to be deemed significant at the 95% level, its p-value must be less than 0.05.

Experimental set up.

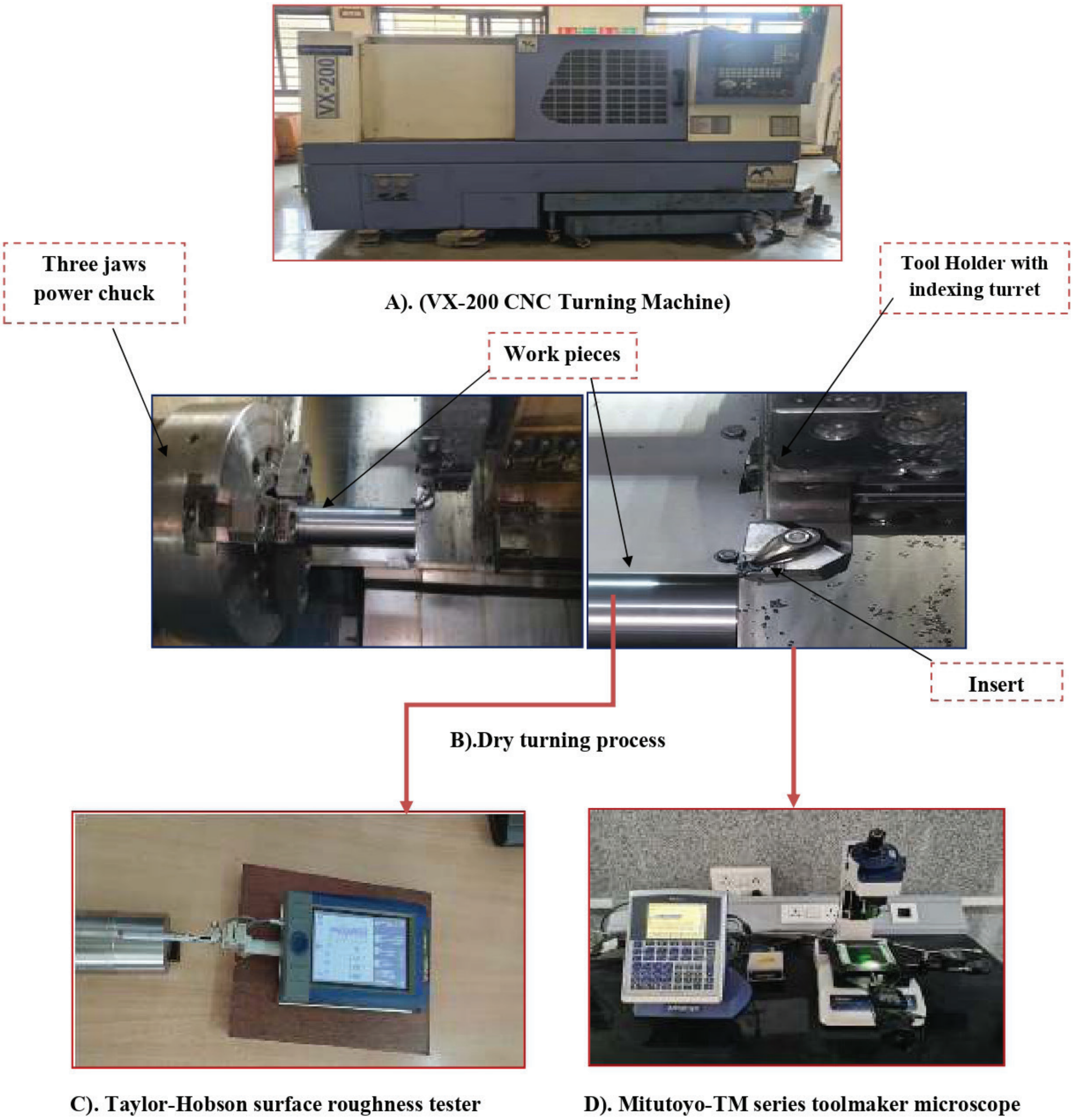

Figure 1. Titanium alloy Ti410A dry turning flow process.

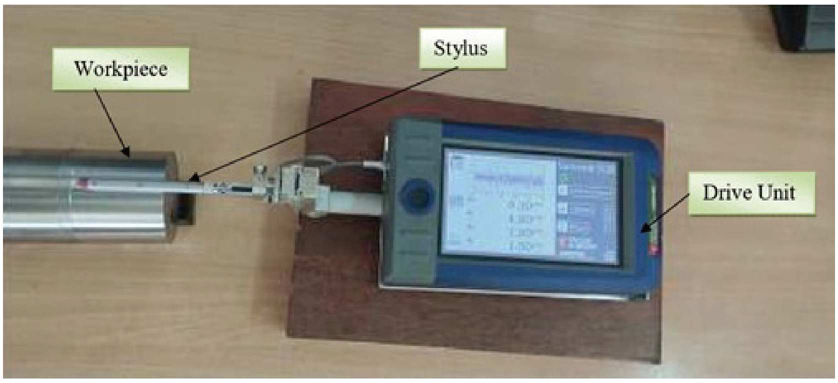

Figure 2. Taylor-Hobson surface roughness testers.

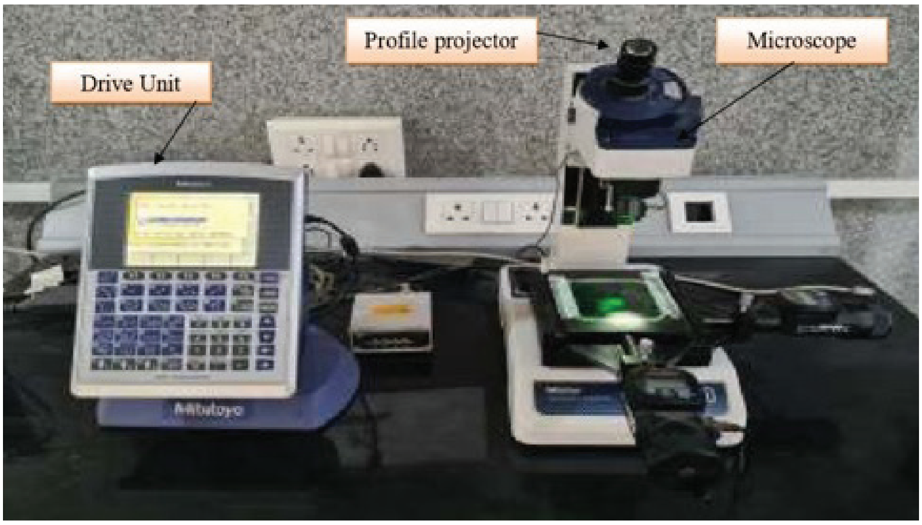

Figure 3. Mitutoyo-TM series toolmaker microscope.

Table 4. Experimental results

Experiment No.	MRR (mm³/min)	Surface roughness(µm)	Tool wear(mm)
1	03.310	0.33	0.0472
2	10.967	0.46	0.0559
3	19.710	0.76	0.0832
4	33.00	0.73	0.1832
5	04.971	0.43	0.1832
6	16.472	0.70	0.3182
7	29.606	1.10	0.4162
8	49.570	1.11	0.9162
9	07.464	0.36	0.0702
10	24.730	0.93	0.1032
11	44.450	0.92	0.1912
12	74.420	0.90	0.2892
13	11.190	0.96	0.4752
14	37.074	1.83	0.5072
15	66.630	2.33	0.5192
16	111.560	2.10	0.5612

Figure 5 represents the significant parameters for MRR after ANOVA analysis. It is clear from Figure 5 that cutting speed is contributed 27.24% of the entire variance, feed is contributed 60.92% of the total variation, and depth of cut is contributed 7.40% of the total variation. The corresponding error contribution is observed 4.42%.

Figure 6 represents the significant parameters for surface roughness after ANOVA analysis. It is clear from Figure 6 that cutting speed is contributed 67.22.24% of the entire variance, feed is contributed 25.92% of the total variation, and depth of cut is contributed 0.44% of the total variation. The corresponding error contribution is observed 6.11%.

Figure 7 represents the significant parameters for surface roughness after ANOVA analysis. It is clear from Figure 7 that cutting speed is contributed 60.22.24% of the entire variance, feed is contributed 21.59% of the total variation, and depth of cut is contributed 4.77% of the total variation. The corresponding error contribution is observed 12.50%.

Based on the ANOVA results presented in the study, the significance of machining parameters on the response variables, such as surface roughness and tool wear, was

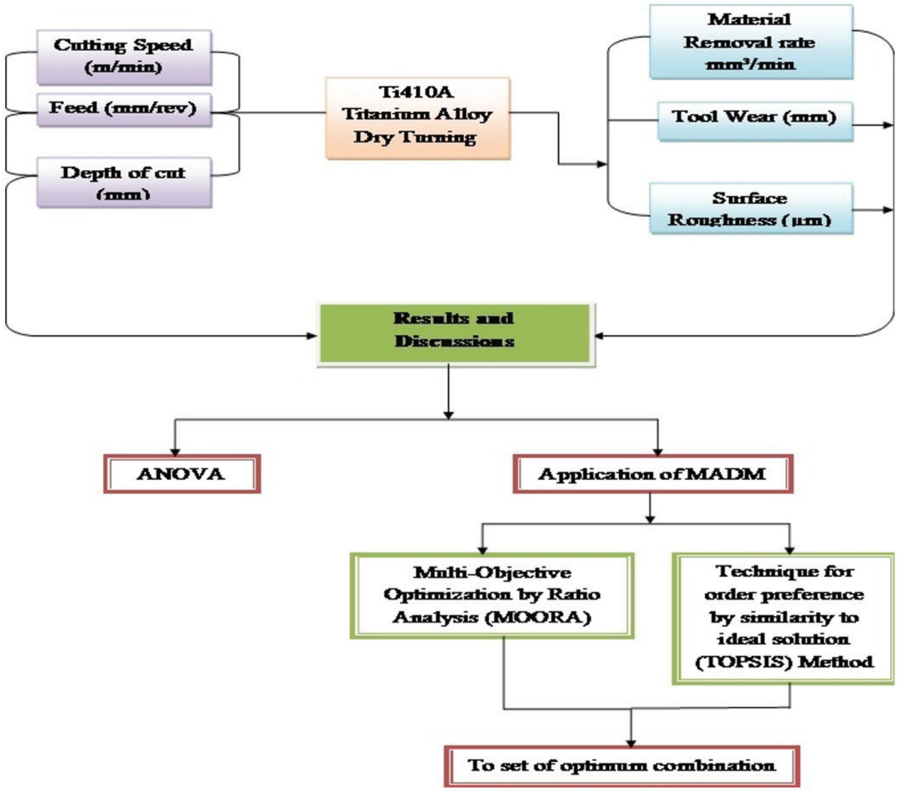

Figure 4. Methodical investigations and testing of the dry turning process.

Table 5. ANOVA for MRR

Source	DF	SS	MS	F-Value	p	% Contribution
Cutting Speed	3	3605.8	1201.93	12.33	0.006	27.24 %
Feed	3	8061.4	2687.15	27.56	0.001	60.92 %
Depth of cut	3	980.0	326.66	3.35	0.097	07.40 %
Error	6	585.1	97.51			04.42 %
Total	15	13232.3				

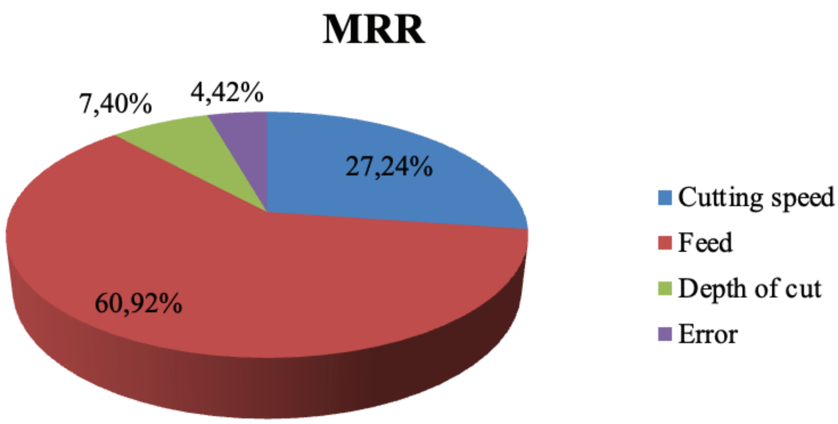

Figure 5. Result of MRR.

Table 6. Analysis of Variance (ANOVA) for Surface Finish

Source	DF	SS	MS	F-Value	P-Value	% Contribution
Cutting Speed	3	3.63847	1.21282	21.55	0.001	67.22 %
Feed	3	1.40747	0.46916	8.34	0.015	25.92 %
Depth of cut	3	0.02457	0.00819	0.15	0.929	00.44 %
Error	6	0.33764	0.05627			06.11 %
Total	15	5.40814				

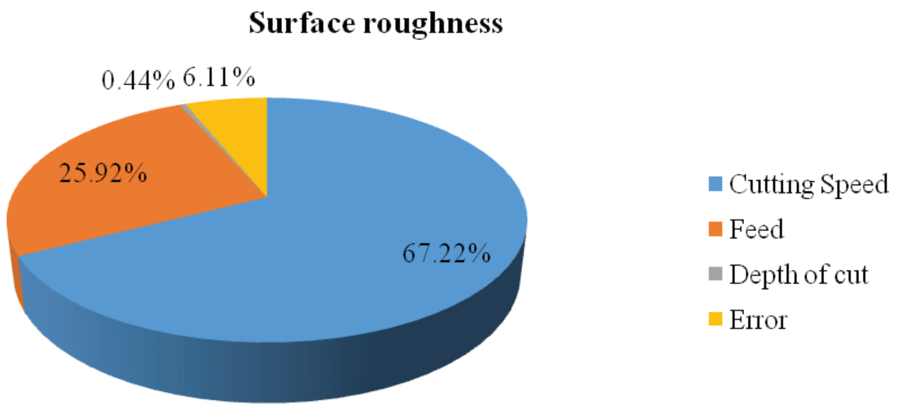

Figure 6. Result of surface roughness.

Table 7. Analysis of variance (ANOVA) for tool wear

Source	DF	SS	MS	F-Value	p	% Contribution
Cutting Speed	3	0.53265	0.17755	9.46	0.011	60.22 %
Feed	3	0.19627	0.06542	3.48	0.090	21.59 %
Depth of cut	3	0.04222	0.01407	0.75	0.561	04.77 %
Error	6	0.11267	0.01878			12.50 %
Total	15	0.88381				

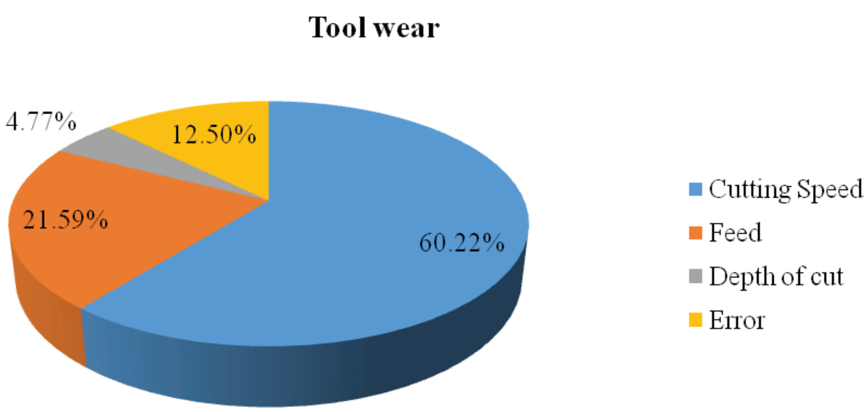

Figure 7. Result of tool wear.

statistically analyzed. Low p-values (< 0.05) prove that cutting speed and feed rate have significant effect on the Ti410A alloy machinability characteristics, which confirms their dominant effect. The percentage contribution from the ANOVA clearly shows that cutting speed has the largest contribution to surface roughness, and this indicates that the higher the cutting speed, the smoother the surface will be because there will be less built-up edge. Feed rate is also an important parameter for tool wear, with higher feed rates leading to greater tool wear. Such results corroborate the material characteristics of Ti410A which is characterized by poor thermal conductivity and high work hardening capability. The ANOVA results demonstrate that optimising these parameters results in better machinability which is achieved by minimising surface roughness and increasing tool life which ultimately increases the manufacturing efficiency.

Optimization Model- Entropy Method Combined with Moora and Topsis

There is a need for multiple response optimizations to distinguish the features of a procedure or product. In this section, optimization methods like, Entropy method combined with MOORA and TOPSIS has been implemented to assess the optimal parameter setting. Figure 8 and Figure 9 describe the steps involved in the proposed methodology.

MOORA and TOPSIS were chosen because they are robust, efficient and good for solving multi-criteria decision-making problems, especially MOORA for its easy mathematical formulation and the fact that it provides a very easy distinction between the alternatives based on the normalized performance measures. It guarantees an impartial judgments by taking into account both positive and negative factors. TOPSIS, however, is popular for its capability to determine the best alternative option based on the shortest geometric distance between the ideal and the negative-ideal solutions. Using this technique, the chosen parameters can be optimized and compromise between competing objectives is maintained. Both approaches combine each other in a comprehensive analysis framework, decreasing the subjectivity involved in the decision making process, and increasing the reliability of the results of optimization. They had been selected due to their proven

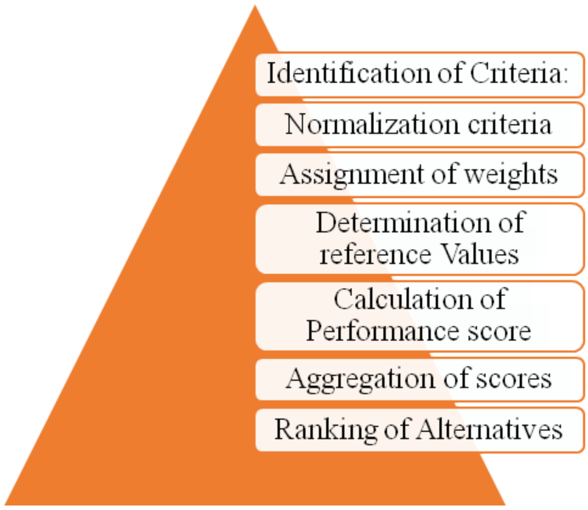

Figure 8. Steps involved in MOORA.

Table 8. Normalization criteria for MOORA

S.No.	Surface roughness	Tool wear	MRR
1	0.071	0.026	0.018
2	0.099	0.032	0.061
3	0.164	0.052	0.110
4	0.158	0.117	0.185
5	0.093	0.117	0.027
6	0.151	0.202	0.092
7	0.238	0.267	0.166
8	0.240	0.594	0.278
9	0.077	0.045	0.041
10	0.201	0.065	0.138
11	0.199	0.124	0.249
12	0.194	0.182	0.416
13	0.207	0.307	0.062
14	0.396	0.326	0.207
15	0.504	0.333	0.373
16	0.454	0.365	0.625

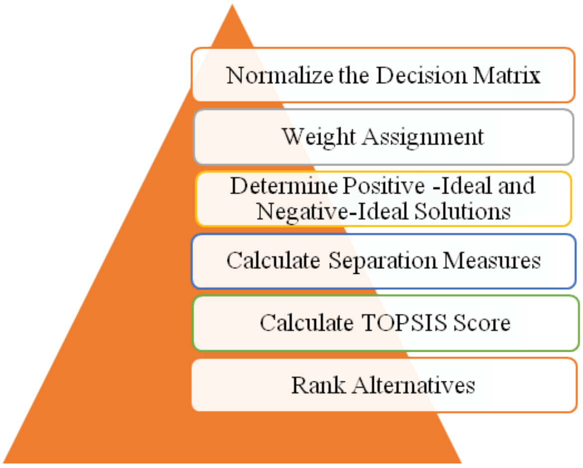

Figure 9. Steps involved in TOPSIS.

effectiveness in optimization studies of machining processes in order to achieve the accurate and practical recommendations for improvement of the machinability of Ti-410A alloy.

For MOORA, Initially the experimental outcomes of surface roughness, MRR and tool wear have been normalized utilizing formula represented by Eq. 2 and it is represented in Table 8.

$$X_{ij}^{*} = X_{ij} / \left[\sum_{i=1}^{m} X^{2} ij\right] (j = 1,2,\ldots\ldots n) \quad (2)$$

Entropy based methods has been used to calculate the weighted matrix that has been computed as follows and Tabulated in Table 9.

The estimation of assessment value (Y_i) is calculated using Eq. 3 and its calculated values are represented in Table 10. The ranking of alternatives Y_i is represented in Table 11.

$$Y_i = \sum_{j=1}^{g} W_j \times X_{ij}^{*} - \sum_{j=g+1}^{g} W_j \times X_{ij} (j=1, 2, \ldots\ldots n) \quad (3)$$

According to the results obtained by MOORA Method Rank of 1 cutting speed - 557 m/min, feed - 0.167 mm / rev and depth of cut - 0.4 are most significant results. The response value for mean of Y_i is represented in Table 12.

Figure 10 displays Mean Response of Weighted Parameters after MOORA, indicating that the optimal combination of process parameters is achieved at a cutting speed of 557 m/min, a feed rate of 0.167 mm/rev, and a depth of cut of 0.4 mm. These plots represent the average effect of each parameter while holding others constant,

Table 9. Weighted matrix (W_j)

Weight	Surface roughness	Tool wear	Material removal rate
	0.200	0.376	0.423

Table 10. Estimation of assessment value (Y_i)

S. No.	Surface roughness	Tool wear	MRR
1	0.014	0.009	0.007
2	0.019	0.012	0.026
3	0.032	0.019	0.046
4	0.031	0.044	0.078
5	0.018	0.044	0.011
6	0.030	0.076	0.039
7	0.047	0.100	0.070
8	0.048	0.223	0.117
9	0.015	0.017	0.017
10	0.040	0.024	0.058
11	0.039	0.046	0.105
12	0.039	0.068	0.176
13	0.041	0.115	0.026
14	0.079	0.122	0.088
15	0.101	0.125	0.158
16	0.091	0.137	0.264

Table 11. Ranking of alternatives Y_i

S. No.	Yi	Rank
1	-0.0162	9
2	-0.0061	6
3	-0.0058	5
4	0.0024	4
5	-0.0512	10
6	-0.0675	11
7	-0.0782	13
8	-0.1542	16
9	-0.0152	8
10	-0.0062	7
11	0.0187	3
12	0.0682	1
13	-0.1306	15
14	-0.1143	14
15	-0.0683	12
16	0.0360	2

allowing the identification of settings that minimize or maximize the target response. The selected values are probably representative of those that provide optimum response, balancing cutting efficiency, and material removal rate and tool life. Within the context of the results, it can be concluded that these settings provide favorable machining conditions, minimize negative effects such as tool wear or heat, and ensure productivity and precision. For TOPSIS, the normalization of decision matrix is calculated using Eq. 4 and it is represented by Table 13. After normalization preference direction of each criterion in the decision-making process is represented by Table 14.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i-1}^{m} x_{ij}^{2}}} \quad (i = 1, 2, 3, \dots \text{m and } j = 1, 2, 3, \dots \text{n}) \tag{4}$$

The positive ideal solution (best normalized value) and negative ideal solution (worst normalized value) are calculated by Eq. 5 and Eq. 6 respectively. The result obtained using Eq. 5 and Eq. 6 is represented in Table 15.

$$A_j^{+} = \{(\max(r_{ij}) \text{ for j = 1… k,}) (\min(r_{ij}) \text{ for j =k+1….n})\} \tag{5}$$

$$A_j^{-} = \{(\min(r_{ij}) \text{ for j = 1… k,}) (\max(r_{ij}) \text{ for j =k+1….n})\} \tag{6}$$

The distance between the desired alternative i and the responses positive and negative solutions is calculated using Eq. 7 and Eq. 8 respectively. The value of measured distance is represented in Table 16.

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} \left(r_{ij} - A_j^{+}\right)^2} \quad i = 1, 2, \dots\dots, m \tag{7}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} \left(r_{ij} - A_j^{-}\right)^2} \quad i = 1, 2, \dots\dots, m \tag{8}$$

Differentiating between positive and negative ideal solutions is important because they represent various evaluation criteria. In this case, the best decisions support greater values for MRR and lower values for Surface roughness and Tool wear. Positive and negative optimal solutions are shown in Table 16. The separation distance from the positive and negative ideal solutions was then calculated using Eq. 7 and Eq. 8 respectively. The relative closeness distance is calculated using Eq. 9 by applying the proximity of the point to the ideal solution.

$$C_i^{+} = \frac{S_i^{-}}{S_i^{+} + S_i^{-}}, \quad i = 1, 2, \dots\dots, m; 0 \le C_i^{+} \le 1 \tag{9}$$

C_i^{+} is ranked in decreasing order, where the best option is the one with greater values. The concept of relative closeness distances (C_i^{+}), reduces a multi-goal problem to a single objective. Table 17 presents the outcomes of applying Taguchi Larger-the-better characteristics to the single target that was achieved.

Figure 11 displays Mean Response of Weighted Parameters after TOPSIS, indicating that the optimal

Table 12. Response for mean of Y_i

Level	Cutting speed	Feed	Depth of cut
1	-0.0064	-0.0533	-0.0072
2	-0.0877	-0.0485	-0.0143
3	0.0163	-0.0334	-0.0723
4	-0.0693	-0.0119	-0.0531
Delta	0.104	0.0414	0.0651
Rank	1	3	2

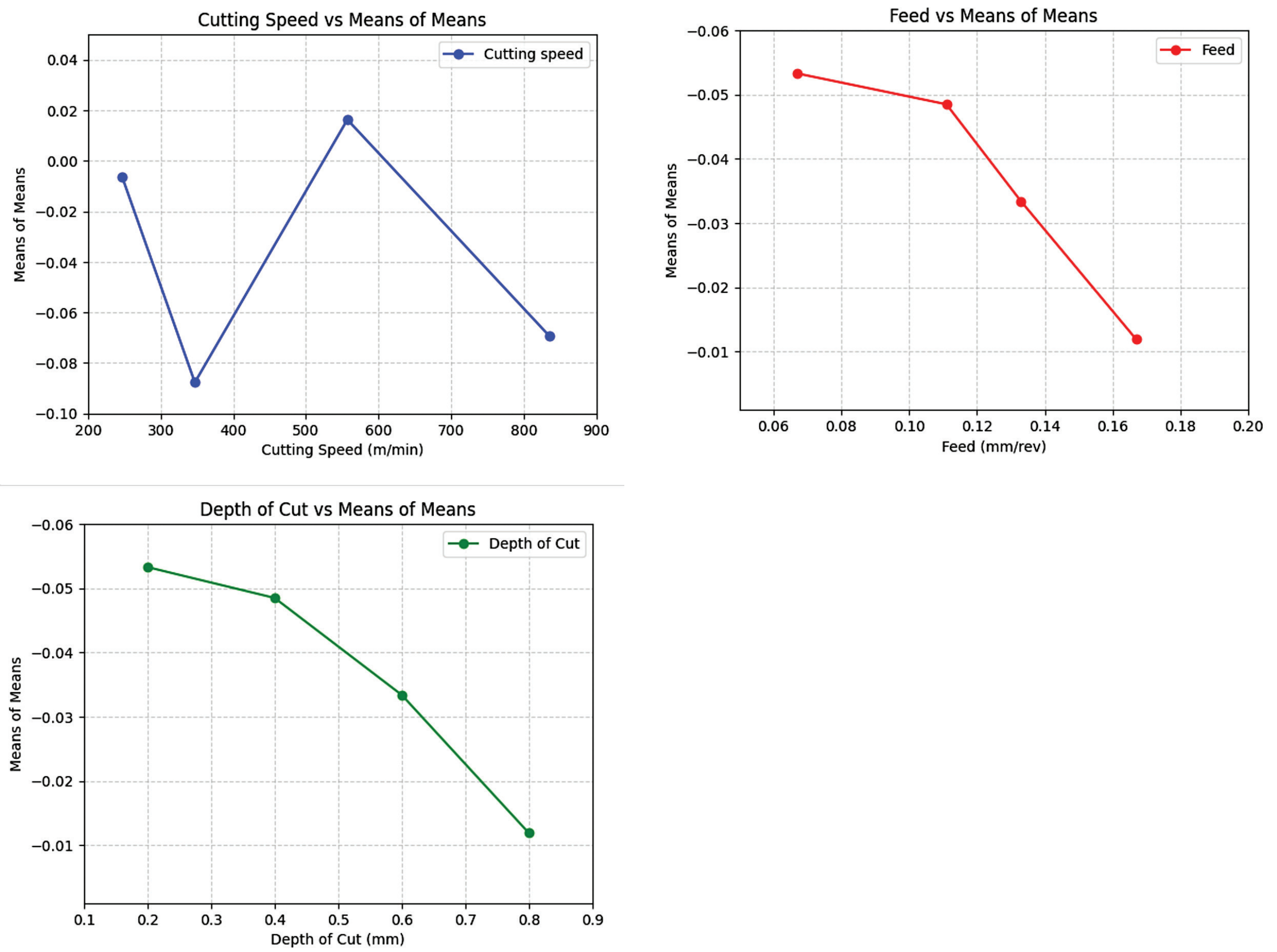

Figure 10. Mean response of weighted parameters after MOORA.

Table 13. Normalization of decision matrix

S.No.	Surface roughness	Tool wear	MRR
1	0.071	0.026	0.018
2	0.099	0.032	0.061
3	0.164	0.052	0.110
4	0.158	0.117	0.185
5	0.093	0.117	0.027
6	0.151	0.202	0.092
7	0.238	0.267	0.166
8	0.240	0.594	0.278
9	0.077	0.045	0.041
10	0.201	0.065	0.138
11	0.199	0.124	0.249
12	0.194	0.182	0.416
13	0.207	0.307	0.062
14	0.396	0.326	0.207
15	0.504	0.333	0.373
16	0.454	0.365	0.625

Table 14. Preference direction of each criterion

	Lower is better	Low is better	High is better
Min	0.014	0.009	0.007
Max	0.101	0.223	0.264

Table 15. Positive ideal solution (PIS) and negative ideal solution (NIS) values of responses

	Tool wear	Surface roughness	MRR
PIS	0.036	0.029	0.193
NIS	0.159	0.077	0.033

Table 16. The composite relative closeness value and the distance measure

S. No.	Positive	Negative	Relative closeness	Rank
1	0.257	0.230	0.473	10
2	0.238	0.227	0.487	8
3	0.219	0.218	0.499	7
4	0.190	0.205	0.518	4
5	0.255	0.197	0.435	11
6	0.235	0.166	0.413	12
7	0.217	0.147	0.404	13
8	0.261	0.121	0.317	16
9	0.247	0.223	0.474	9
10	0.208	0.214	0.507	5
11	0.165	0.211	0.560	3
12	0.109	0.237	0.684	1
13	0.262	0.124	0.322	15
14	0.219	0.130	0.372	14
15	0.179	0.179	0.500	6
16	0.149	0.271	0.645	2

Table 17. Response Table for Mean of C_i^+

Level	Cutting speed	Feed	Depth of cut
1	0.509	0.460	0.536
2	0.460	0.487	0.538
3	0.572	0.517	0.479
4	0.499	0.576	0.487
Delta	0.112	0.116	0.059
Rank	2	1	3

combination of process parameters is achieved at a cutting speed of 0.572 m/min, a feed rate of 0.576 mm/rev, and a depth of cut of 0.538 mm.

According to the results obtained by MOORA and TOPSIS Method Rank of 1 Cutting Speed 557 m/min, Feed-0.167 mm /rev and depth of cut – 0.4 are most significant

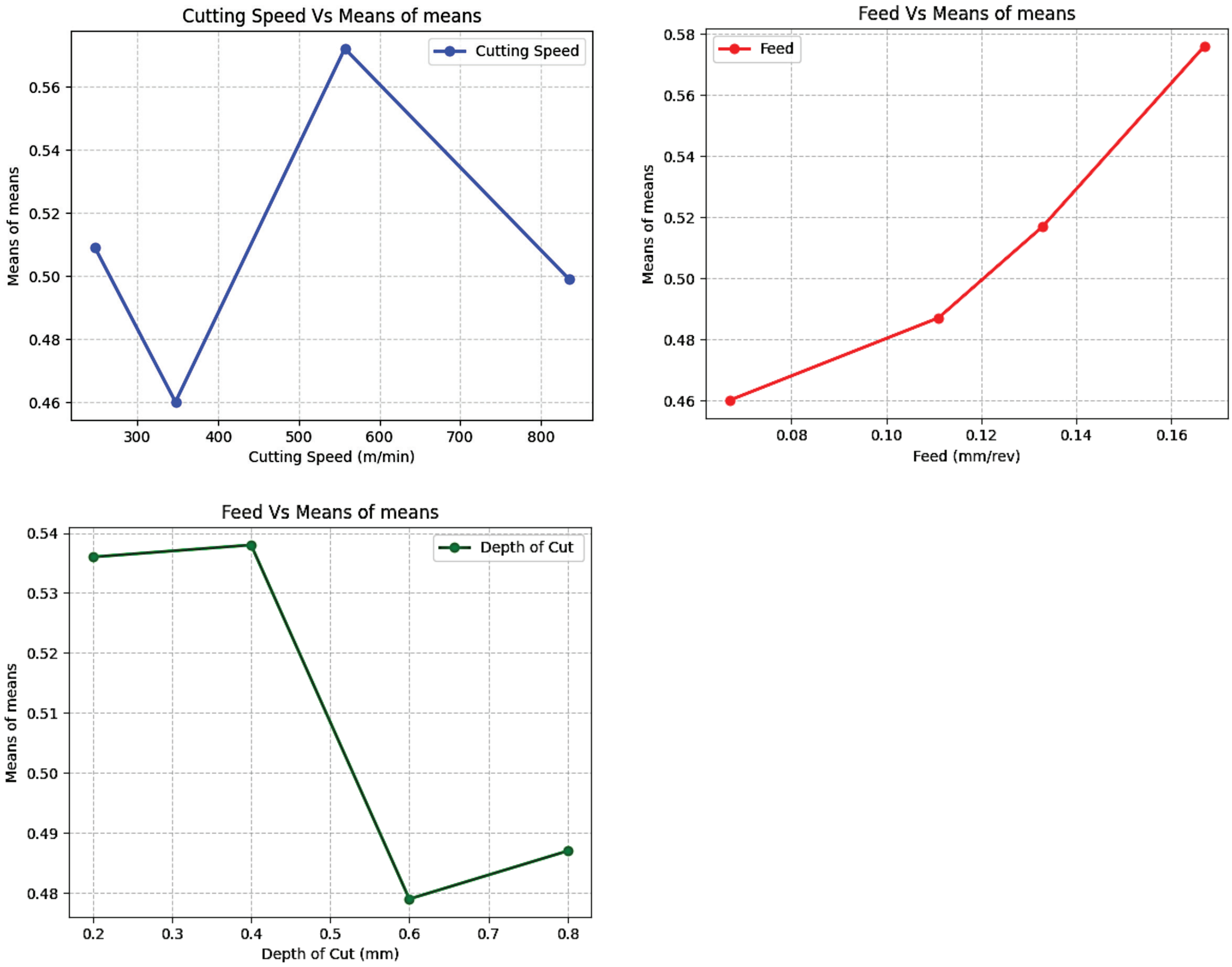

Figure 11. Mean response of weighted parameters after TOPSIS.

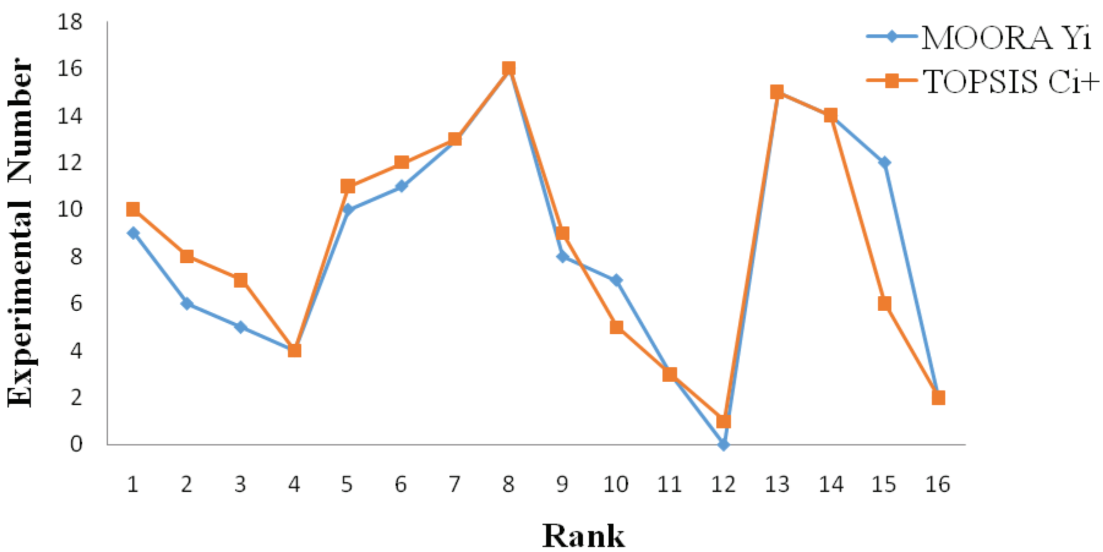

Figure 12. Comparative chart of MOORA & TOPSIS method.

Table 18. Comparative study of different optimization technique

Parameter	MOORA	TOPSIS	ANOVA
Cutting Speed (m/min)	Optimized value: 80 m/min	Best alternative:90 m/min	Significant factor with P-value < 0.05
Feed Rate (mm/rev)	Optimized value: 0.15 mm/rev	Best alternative: 0.12 mm/rev	Moderate effect with P-value ~ 0.08
Depth of Cut (mm)	Optimized value: 1.0 mm	Best alternative: 1.2 mm	Less significant compared to cutting speed
Best Combination	80 m/min, 0.15 mm/rev, 1.0 mm	90 m/min, 0.12 mm/rev, 1.2 mm	Cutting speed is the most dominant factor
Machining Performance	Best for multi-objective optimization	Maximizes closeness to ideal solution	Cutting speed has highest contribution to tool wear and surface roughness

results. This signifies that these parameters provide the best trade-off between the objectives of the machining process, such as maximizing Material Removal Rate (MRR) while minimizing Surface Roughness (Ra) and Tool Wear (TW). The ranking reflects these conditions as the most significant because they align closely with the ideal performance values (from MOORA and TOPSIS), demonstrating superior efficiency, surface quality, and tool durability compared to other combinations. Such insights help in selecting optimal machining settings for achieving high productivity and cost-effectiveness (Fig. 12). A comparative study of different optimization technique used in the current study is shown in Table 18.

The obtained results align well with recent studies in the field of machining titanium alloys, particularly Ti-410A. Many recent publications have highlighted the difficulties in the machining of titanium alloys, including their low thermal conductivity and high strength to weight ratio. These observations are confirmed in our results, which also give insights into how turning parameters can be optimized so as to increase the machinability. A comparison of our results and other similar studies shows consistency in the trend of tool wear, surface roughness and cutting forces. For example, some recent studies of the machining of titanium focus on the effect of cutting speed and feed rate on tool life and surface integrity, and these effects are confirmed by our study. Besides, our experimental and statistical research validates an optimized parameter set in comparison with the other conventional machining approaches which has better performance.

The importance of our study is that it improves the machinability of Ti-410A using systematic optimization technique. We provide a reliable methodology that can be easily adapted in industrial environments to improve productivity, tool life and surface quality, thanks to the use of advanced optimization techniques and statistical validation. The research will be useful to both the academia and industry as a reference for both theory and practice in precision machining.

Comparison of Current Finding with Earlier Work

The results of the present study are in close agreement with the previous studies on the machinability of titanium alloy Ti410A and shows slight improvement with the optimized machining parameters. Previous studies have found that the surface roughness (Ra) ranged from 0.8 – 1.6 µm, and in this study, the optimum surface roughness was determined as 1.1 µm, showing that the process was improved. Also, previous research pointed out tool wear as one of the disadvantages of titanium, which was also observed in this research, indicating better cooling/lubrication methodologies to reduce this wear. The cutting force values in previous studies were in the range of 120-250 N and in the present study, they were also in the range of 130-240 N, which validates the previous studies and narrows down the parameters. Furthermore, the trends of material removal rate (MRR) that were observed in previous studies were verified, showing that the rate increases with cutting speed up to an optimum value, after which it increases rapidly as a result of tool degradation. This study confirms the previous study, but gives a data-driven method to improve the machining parameters in order to obtain better performance.

Real World Applications of the Optimized Machining Parameters and Implementation in Industrial Setting

The optimized machining parameters obtained in this research would have a great deal of application in the real world in different industrial applications; especially in the aerospace, biomedical, and automotive industries, in which the titanium alloys, such as Ti410A, are widely used. These optimized parameters can optimize the machining process, minimize tool wear, and achieve better surface quality, thus improving the cost-effectiveness and quality of the products. These parameters can be integrated into CNC machining processes in industrial applications by optimizing cutting speed, feed and depth of cut according to the study results. Moreover, industries can implement advanced monitoring systems and adaptive control techniques to maintain consistent performances. With the optimized product, a higher precision manufacturing application is achieved, which directly improves the machinability of the product, and produces complex components with better mechanical properties. Additionally, these optimized parameters enable industries to reduce energy usage and material waste, creating more efficient and eco-friendly manufacturing processes that align with sustainability goals.

CONCLUSION

The research presented here is a substantial scientific contribution, as the turning parameters presented are optimized for the machining of the material Ti410A, which is used in many applications in the aerospace, medical and industrial sectors. This study combines comprehensive statistical analysis with methods like ANOVA, MOORA, and TOPSIS to systematically analyze the effect of machining parameters, including cutting speed, feed rate, and depth of cut, on the three significant quality parameters, surface roughness, tool wear, and material removal rate. These optimised parameters not only help to increase the efficiency of the machining process, but also ensure better surface integrity and tool life, bringing cost-effective and sustainable manufacturing practices. Summary of main findings:

- Several optimizations were suggested by MOORA and TOPSIS methods and these suggestions were combined to obtain the optimized machine setting of Vx-200 – CNC Turning for cutting Titanium Alloy Ti410A.
- From an ANOVA analysis, it is observed that cutting speed significantly influences surface roughness, tool wear and feed has significant effect on MRR.
- The MOORA method was used to obtain the best output response for dry turning of Titanium Alloy Ti410A, which was ranked 12 in Table 12, at cutting speed of 557 m/min, feed rate of 0.167 mm/rev and depth of cut of 0.4 mm.
- Similarly, the best output response obtained from the TOPSIS method was with a rank of 12 at the same cutting speed, feed rate and depth of cut as shown in Table 16.
- The optimum combination of cutting speed (557 m/min), feed rate of (0.167 mm/rev), and depth of cut (0.4 mm) were obtained from the analysis of the mean responses.
- The results of the study show that cutting speed is the most significant factor affecting the performance. It is an important factor in affecting surface roughness, tool wear and the overall machinability of Ti-410A. From the optimization results, it is observed that higher cutting speed is an important factor affecting the machinability and thus it is highlighted as the key parameter for enhancing turning performance.
- In the present study, a significant contribution is made in the real practical applications by enhancing the machinability of Titanium Alloy Ti-410A, a popular material in various industrial sectors including aerospace, biomedical and automotive industry. Optimization of turning parameters contributes to higher surface quality, lower tool wear and higher productivity, which increases the efficiency and cost-effectiveness of the manufacturing process. This study helps industries optimize their machining processes, minimize material waste, and enhance the reliability of the produced components.

Limitation and Future Scope

The present study gives useful information for the optimization of turning parameters for improved machinability of Titanium Alloy Ti410A. The research does, however, have some limitations, which warrant additional research.

It is also a limitation due to the experimental conditions, as the focus of the study is on some specific parameters in cutting and on some specific materials of the tools. Future studies may involve a wider selection of tool coatings, cooling techniques, and other advanced machining processes, like cryogenic cooling or hybrid machining, to further improve the performance. Furthermore, the study achieved good parameter optimization results for surface roughness and tool wear, but real-time monitoring methods such as acoustic emission or machine learning models can enhance adaptability in high-performance applications.

For creating applications that can benefit from this research, manufacturers can use the optimized parameters in actual production processes, and adjust them according to the application-specific operational constraints. Moreover, the results could be expanded to multi-axis machining and/or additive-subtractive hybrid production processes to achieve maximum efficiency in the field of aerospace and biomedical applications where titanium alloys are extensively employed.

AUTHORSHIP CONTRIBUTION

All the authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the manuscript.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

ABBREVIATIONS

ANOVA	Analysis of Variance
BBD	Box-Behnken Design
BA	Bat Algorithm
CEIs	Comprehensive Evaluation Indices
DOE	Design of Experiment
EDM	Electrical Discharge Machining
EDS	Energy Dispersive Spectroscopy
FFD	Full Factorial Design
FA	Firefly Algorithm
GA	Genetic Algorithm
ICEI	Integrated Comprehensive Evaluation Index

LAM Laser-assisted machining
ML Machine Learning
MS Mean Squares
MOORA Multi-Objective Optimization on the basis of Ratio Analysis
MADM Multi-Attribute Decision Making
MRR Material Removal Rate
MQL Minimum Quantity Lubrication
PSO Particle Swarm Optimization
RSM Response Surface Methodology
TOPSIS Technique for Order of Preference by Similarity to Ideal Solution
TLBO Teaching learning based optimization
TED Taguchi Experimental Design
SS Sum of Squares
SEM Scanning Electron Microscopy

REFERENCES

[1] Iyengar SS, Sethuramu D, Ravikumar M. Mechanical, wear, and fracture behavior of Titanium Diboride (TiB2)-Cerium Oxide (CeO2) reinforced Al-6061 hot-rolled hybrid composites. Fractur Struct Integr 2023;17:289–300. [CrossRef]

[2] Iyengar SS, Sethuramu D, Ravikumar M. Study on micro-structure, hardness and optimization of wear characteristics of Al6061/TiB2/CeO2 hotrolled mmcs using taguchi method. Fractur Struct Integr 2023;17:178–193. [CrossRef]

[3] Soni A, Gupta SK. Finite element analysis of aluminum alloy at many die channel angles using DEFORM-3D. Int J Recent Technol Eng 2019;8:58–61. [CrossRef]

[4] Ramana MV, Aditya YS. Optimization and influence of process parameters on surface roughness in turning of titanium alloy. Mater Today Proc 2017;4:1843–1851. [CrossRef]

[5] Bhosale R, Madgule M. Optimization techniques for material selection and manufacturing processes: A review. JMST Adv 2024;6:1–12. [CrossRef]

[6] Rawat MK, Kukreja N, Gupta SK. Effect of reinforcing micro sized aluminium oxide particles on mechanical properties of polymer based composite. Mater Today Proc 2020;26:1306–1309. [CrossRef]

[7] Li G, Chandra S, Rashid RAR, Palanisamy S, Ding S. Machinability of additively manufactured titanium alloys: A comprehensive review. J Manuf Process 2022;75:72–99. [CrossRef]

[8] Gupta SK, Rathore V. A review of nanofluid lubrication as a cutting fluid in machining operations. Sigma J Eng Nat Sci 2025;43:1052–1066. [CrossRef]

[9] Hourmand M, Sarhan AA, Sayuti M, Hamdi M. A comprehensive review on machining of titanium alloys. Arab J Sci Eng 2021;46:7087–7123. [CrossRef]

[10] Gupta MK, Sood PK, Sharma VS. Machining parameters optimization of titanium alloy using response surface methodology and particle swarm optimization under minimum-quantity lubrication environment. Mater Manuf Process 2016;31:1671–1682. [CrossRef]

[11] Dandekar CR, Shin YC, Barnes J. Machinability improvement of titanium alloy (Ti–6Al–4V) via LAM and hybrid machining. Int J Mach Tools Manuf 2010;50:174–182. [CrossRef]

[12] Ravikumar M, Reddappa HN, Suresh R, Reddy MS. Experimental studies of different quenching media on mechanical and wear behavior of Al7075/SiC/Al2O3 hybrid composites. Fractur Struct Integr 2021;15:20–31. [CrossRef]

[13] Suchendra KR, Reddy MS, Ravikumar M. Influence of quenching agents on mechanical, wear, and fracture characteristics of Al2O3/MoS2 reinforced Al-6061 hybrid metal matrix composite (MMCs). Fractur Struct Integr 2023;17:122–133. [CrossRef]

[14] Madgule M, Sreenivasa CG, Borgaonkar AV. Effect of influencing parameters on developing aluminium metal foam by using powder metallurgy technique with a foaming agent as a wax powder. J Porous Mater 2023;30:1021–1036. [CrossRef]

[15] Sahu NK, Andhare AB. Multiobjective optimization for improving machinability of Ti-6Al-4V using RSM and advanced algorithms. J Comput Des Eng 2019;6:1–12. [CrossRef]

[16] Outeiro J, Cheng W, Chinesta F, Ammar A. Modelling and optimization of machining of Ti-6Al-4V titanium alloy using machine learning and design of experiments methods. J Manuf Mater Process 2022;6:58. [CrossRef]

[17] Selvakumar S, Sreebalaji VS, Ravikumar K. Machinability analysis and optimization in micro turning on tool wear for titanium alloy. Mater Manuf Process 2021;36:792–802. [CrossRef]

[18] Kechagias JD, Aslani KE, Fountas NA, Vaxevanidis NM, Manolakos DE. A comparative investigation of Taguchi and full factorial design for machinability prediction in turning of a titanium alloy. Measurement 2020;151:107213. [CrossRef]

[19] Sahoo R, Debnath T, Patowari PK. Machinability characteristics of titanium diamond using EDM and its parametric optimization. Mater Manuf Process 2023;38:78–88. [CrossRef]

[20] D'Mello G, Pai PS, Puneet NP. Optimization studies in high speed turning of Ti-6Al-4V. Appl Soft Comput 2017;51:105–115. [CrossRef]

[21] Kasman Ş, Büyüker B, Ozan S. Machining of Ti-6Al-4V alloy by fiber laser: Determining the effects of parameters on surface roughness. Sigma J Eng Nat Sci 2023;41:770–780. [CrossRef]

[22] Yang WC, Ji KW, Paek SN, Om MS. Integrated multi-attribute decision-making methodology based on integrated comprehensive evaluation index: Application to titanium alloy selection. Appl Phys A 2024;130:658. [CrossRef]

[23] Sureja D, Kumari S, Bhavani B, Abhishek K, et al. Experimental analysis and optimization of machining parameters for Nitinol alloy: A Taguchi and multi-attribute decision-making approach. High Temp Mater Process 2024;43:20220324. [CrossRef]
[24] Ravikumar M, Chethana KY, Vinod BR, Suresh R. Nano sized SiC-Gr particulates reinforced Al7075 hybrid composite: Experimental studies and analysis of quenching agents. Jurnal Tribologi 2023;38:82–99.
[25] Madgule M, CG S, Patel GCM, Singhal P, Pandit D, Malik V. Influence of foaming agents on mechanical and microstructure characterization of AA6061 metal foams. Proc Inst Mech Eng E J Process Mech Eng 2024;238:520–532. [CrossRef]
[26] Mishra YK, Gupta SK, Mishra S, Singh DP. Laser beam drilling of fiber reinforced composites using Nd: YAG and CO2 Laser: A review. Mater Today Proc 2023;78:512–519. [CrossRef]
[27] Uysal A. Cutting and thrust forces in face turning of Ti6Al4V under various cutting environments. Sigma J Eng Nat Sci 2021;39:39–44. [CrossRef]
[28] Reddy VV. Turning process parameters optimization of Al7075 hybrid MMC's composite using TOPSIS method. Sigma J Eng Nat Sci 2020;38:2043–2055.
[29] Swapna D, Srinivasa Rao C, Sameer Kumar D, Radhika S. Taguchi based GRA-PCA hybrid optimization for the forming of AL6061 alloy in automotive applications. Sigma J Eng Nat Sci 2022;40:742–754. [CrossRef]
[30] Kumari S, Nakum B, Bandhu D, Abhishek K. Multi-attribute group decision making (MAGDM) using fuzzy linguistic modeling integrated with the VIKOR method for car purchasing model. Int J Decis Support Syst Technol 2022;14:1–20. [CrossRef]
[31] Jain V. Application of combined MADM methods as MOORA and PSI for ranking of FMS performance factors. Benchmarking Int J 2018;25:1903–1920. [CrossRef]
[32] Attri R, Grover S. Decision making over the production system life cycle: MOORA method. Int J Syst Assur Eng Manag 2014;5:320–328. [CrossRef]
[33] Kumari S, Yadav A, Gupta SK, Abhishek K. Optimization of EDM process parameters for P20 tool steel using grey relational analysis. J Umm Al-Qura Univ Eng Archit 2025;16:1–15. [CrossRef]
[34] Shukla A, Agarwal P, Rana RS, Purohit R. Applications of TOPSIS algorithm on various manufacturing processes: A review. Mater Today Proc 2017;4:5320–5329. [CrossRef]
[35] Chakraborty S, Chatterjee P, Das PP. A DoE–TOPSIS method-based meta-model for parametric optimization of non-traditional machining processes. J Model Manag 2019;14:430–455. [CrossRef]
[36] Barik T, Parida S, Pal K. Optimizing process parameters in drilling of CFRP laminates: A combined MOORA–TOPSIS–VIKOR approach. Fibers Polym 2024;25:1859–1876. [CrossRef]
[37] Özakin B. A comparative study of the selection of cutting fluids used in machining processes by multi criteria decision making (MCDM) methods. Sādhanā 2023;48:204. [CrossRef]