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Experimental Analysis and Forecasting of 17-4PH Steel in Turning Operations through TiAlN Tool Insert by Employing Artificial Neural Network and Rice Bran Oil for Sustainable Manufacturing

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Abstract

Sustainable manufacturing aims to boost output while utilizing fewer resources, cutting costs, and having a smaller negative impact on the environment. Regarding the expenditure of materials, power, and resources required for creation as well as the prices of manufacturing processes, the longevity of tools used in machining operations is one of the most crucial variables in this context. The necessity to remove the produced chips, the excessive heat produced during the process, or the friction among the tool and the workpiece are all potential causes. Cutting fluid is often used to lower cutting temperatures, lower friction among the tool and the work piece, add to tool life, and enhance surface quality and machining efficiency. The current research focuses on using rice bran oil as a cooling agent to produce minimum friction and reducing the cutting forces by using a TiAlN tipped tool. Taguchi's robust design was used to minimize the number of trials by means of L-9 orthogonal array. Speed (m/min), feed (mm/rev), depth of cut(mm), and rice bran oil (ml/min), were chosen as controllable process factors in the turning process, and surface roughness was engaged into consideration as performance evaluation features. The Taguchi analysis that revealed the appropriate process parameters markedly increased the turning performance when turned 17-4 PH, according to the results of the conformation tests. The rice bran oil used as a cutting fluid had significantly reduced the frictional forces and the tool insert could manage to cut all the nine samples with improved surface which leads to sustainable products. The Ra was mostly dependent on feed rate and rice bran oil with the respective percentage contributions of 58.06% and 49.5% respectively.

Keywords: Sustainable machining**,** Orthogonal array, Coated insert, Cutting fluid, ANN, and Taguchi Technique.

1. Introduction

Saving energy and natural resources is the most significant component of sustainable manufacturing. Environmentally friendly processes that maximize benefits to the environment are growing increasingly crucial for modern industrialization. Sustainability and environmental concerns are rising to the top of the priority list for protecting biodiversity and natural resources as a result of fast industrialization and economic growth (Hariyaniet al.,2023).There are numerous approaches to minimize pollution, pollutants, and waste in machining: employing greener cooling techniques; implementing strategies that minimize or do away with the requirement for cooling lubricant usage; enhancing the energy efficiency of machining activities(Pimenovetal.,2023). Sustainable manufacturing (Sivaiah et al., 2019) intends to promote output while utilizing fewer resources, cutting costs, and having a smaller negative impact on the environment. The manufacturing process's course and the many aspects explaining the impacts of limited tool life are among the most crucial (Abbas et al., 2019). Here, even a little improvement in the tool's life has the prospective to improve both the final product and the production process in general and lower manufacturing costs. The article shows the findings that were conducted to create a relatively simple method for machining 17-4 PH steel using Al2O3 nano particles and a TiAlN insert on a CNC lathe. The main impact of this method was to increase the life of the tool while preserving the required product quality. Making and producing novel tool materials is an intriguing challenge that should be planned over time rather than as a quick fix to the issue of rising tool costs(Venkatalaxmi et al., 2004).The 17-4PH material appeared to be isotropic based on the results of hardness testing conducted in all three axes (Egseth, 2023).Though it is difficult to machine, 17-4PH steel is particularly valued in defence and aerospace industries due to its exceptional mechanical qualities and excellent balance of corrosion resistance (Yurtkuranet al., 2023). One of the studies highlight the significance of surface nano modification in obtaining multifunctional nano platforms with excellent surface performance for biomedical applications (Beközet al., 2023). The characteristics and structural makeup of 17-4PH made machining challenging and lubricants necessary (Venkatalaxmi et al., 2004). In this situation, the tool tips (Warcholinskiet., al 2011) plastic deformation frequently happens and considerably impairs the cutting characteristics. Therefore, it is essential to shield the tool from severe wear. The tool's working surfaces could be modified with a strong, wear-resistant coating as a potential remedy to this issue. The pace of friction among the chip and the tooltip is significantly decreased during machining when LN2 is sprayed (Hong et al., 2001). The metal-cutting ability of 17-4 PH base metal procedures has only been somewhat investigated by researchers (Khani et al., 2015). When this type of low thermal conductivity material is machined, the machining zone experiences high cut temperatures, which reduce tool life, higher cutting forces, and lesser surface quality. Traditional cutting fluids (Sharma et al., 2009) have been employed for many years to combat the high temperatures at the machine. Typical cutting fluids include chemical pollutants that are dangerous to humans and the atmosphere, and they were unable to control the temperature in the machining area at greater cutting speeds, which led to increased tool wear and decreased productivity. For machinists, health issues can include cancer, breathing issues, and respiration ailments. Additionally, MQL machining is impractical for use in industry conditions because it cannot cut chips from the machining zone and results in health issues for the machinist due to the presence of mists and pollutants. It causes health issues for the machinist as a result of (Aoyama et al., 2008).

According to a literature review, there is not enough information about machining 17-4 PH steel in a sustainable environment. According to the literature, utilising rice bran oil as a cutting fluid enhances chip breakability, surface finish, and tool life when working with hard-to-cut materials.

When used in metalworking and machining operations, rice bran oil has several benefits. Because it is a bio-based lubricant, it is environmentally friendly, has excellent temperature stability, and low viscosity for effective coverage. Its application might be economical, provide anti-wear qualities, and enhance surface finish. Before being widely used in commercial environments, extensive testing is advised as the effectiveness may differ depending on certain circumstances. Hence the outcomes of the turning operation are compared using a mathematical model that is created. The obtained models might be applied to machining selection to evaluate result quality. The best machining parameters show that for low surface roughness, feed and rice bran oil was the majority important machining parameter, followed by machining speed.

Using Taguchi's suggested L-9 orthogonal array (Koyee et al., 2014), the test piece specimen was put through three different degrees of speed, feed, cooling oil, and depth of cut. It is a robust design tool that uses an orthogonal array to accommodate numerous design parameters at once and the S/N ratio to compute quality with a prominence on variance to provide an easy and efficient move towards to design optimization for performance, quality, and associated cost (Choi et al., 2019).

By applying advanced analytics to industrial data and leveraging machine learning and artificial intelligence, manufacturers can get an understanding of maximizing the productivity of individual assets as well as the entire manufacturing operation. (Kosuri et al.,2022; Rao et al.,2022).Researchers have employed artificial neural networks (ANNs) extensively for modeling in a variety of fields, including machining. ANN model, however, is dependent on numerous elements, including network topology, training and testing data. (Sarkar et al., 2019; Sarkar et al., 2020). ANN models have been employed by a number of academics to gain an understanding of the appropriate factors influencing ANN models and the capabilities of ANN modeling for processes in a diversity of domains. (Sarkar et al., 2020; Sarkar et al., 2017). The experimental work has been performed at Uttaranchal University, mechanical engineering department.

2. Methods

A machine known as the "MTAB FLEX Turn" was used to machine the 17-4 PH workpiece material. Table 2.1 shows the experimental information that was taken into consideration for this study. A cutting insert was chosen for turning the 17-4 PH in accordance with the advice of the tool manufacturer. Experiments have been conducted using the Taguchi L9 orthogonal array design since it lowers experimental costs and effort. Table 2.1 lists the acquired experimental results.

During material cutting, heat can be dispersed more effectively with the help of nanofluids because of their superior thermal conductivity over conventional lubricants. A base fluid can be mixed with nano particles to create a colloidal suspension. Their excellent thermal conductivity and viscosity make them a good substitute for thermally conductive fluids; their cooling and lubricating qualities could be improved further by adding nano-additives (Ross et al., 2023).When cutting fluid based on ionic liquid was compared to neat rice bran oil, it achieved significantly improved thermos-physical and tribological capabilities (Singh et al., 2022).In machining, rice bran oil which is mixed with Al2O3, nano powder which is non-hazardous ingredient was utilized as a coolant. The low viscosity, temperature stability, affordability, anti-wear qualities, and enhanced surface smoothness, rice bran oil coolant was utilized in machining (Singh.et al., 2022). With the help of an external nozzle, the coolant was sprayed onto the machine. For the purpose of calculating the machined surface's arithmetic mean surface roughness (Ra) value, a surface roughness tester with a calibrated Profile gauge 0-1000 microns was utilized.

Here, 70 mm long and 40 mm diameter of 17-4 PH steel were used in the current study figure 6 and 7. The orthogonal L9 array, proposed by Taguchi, was used to evaluate the test piece under three parametric models namely, speed, feed, and depth of cut (Riccardiet al., 2022). It is a robust design tool that makes use of orthogonal arrays, which can handle multiple design aspects at once, and S/N ratio, which assesses features with highlighting on variance, intends to offer a simple and structured method for optimizing plans for quality, performance, and related costs. In order to design experiments, Taguchi orthogonal arrays are used. Surface roughness was shown to decrease at the Taguchi-determined ideal cutting condition.

To develop and assess the parameters for efficient optimum results, Minitab 17 software is employed. Using carbide-tipped tools with a positive and negative rake angle, turning operations were carried out (Elangovan et al., 2010; Krolczyk et al., 2015). Comparing the data, it was shown that surface roughness values increase at high cutting parameter values and decrease when the best machining conditions are utilized. As the feed rate was raised, the work piece exhibited greater resistance, which resulted in the creation of edges that were added to the tool face and a reduction in surface finish (Braham-Bouchnak et al., 2010). The Taguchi approach was used to discover the finest cutting parametric combination for getting low surface roughness, and it was established that this combination resulted in a 52.6 percent fall in surface roughness**.** Figure 1 shows the process flow diagram

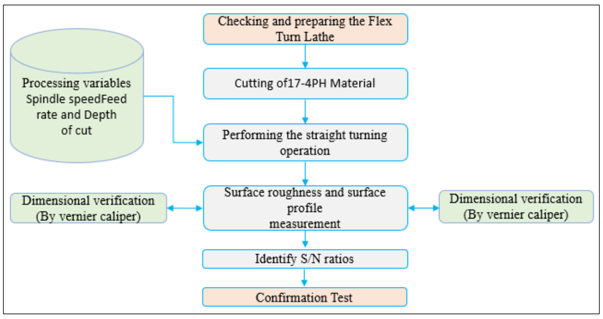

Figure1. Process flow diagram

2

.1 ANN Model Influencing Factors

Studies on the modeling and monitoring of machining operations using artificial neural networks (ANNs) have become more and more popular. The cutting conditions, which are speed (m/min), feed (mm/rev), depth of cut (mm), and rice bran oil (ml/min), are the inputs of the neural network while the surface roughness was output.

Researchers frequently employ ANN for modelling purposes in a variety of fields, including machining (Li et al., 2018;). The surface roughness of 17-4PH steel has been predicted using ANN modelling in this work. The ANN parameters were chosen by means of the following criteria: learning rate of 0.14; momentum rate of 0.05; testing data of 22/5 and network structure of 3-7-1 value (Ezugwu et al., 2005). Table 2.2 displays the data set's predicted outcomes. The f and t tests from table 2.3 shows that the neural network forecasts generally fall pretty near the investigational value

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s (m/min)	f (mm/rev)	d (mm)	Rice Bran oil(ml/min)	(Ra)	SNRA
102	0.1	0.2	100	1.3	-2.27887
102	0.12	0.4	120	1.231	-1.80516
102	0.18	1	150	1.456	-3.26323
125	0.1	0.4	150	1.123	-1.0076
125	0.12	1	100	1.543	-3.76732
125	0.18	0.2	120	1.734	-4.78098
175	0.1	1	120	1.342	-2.55505
175	0.12	0.2	150	1.185	-1.47437
175	0.18	0.4	100	1.872	-5.44612

Table 2.2 Experiment and Forecasted standards of surface roughness using ANN

Sample No.	Ra (µm) Experimental	Ra (µm) ANN	Error (%) j
1	1.3	1.282	1.385
2	1.231	1.249	1.462
3	1.456	1.563	7.349
4	1.123	1.427	27.07
5	1.543	1.378	10.693
6	1.734	1.736	0.115
7	1.342	1.387	3.353
8	1.185	1.158	2.278
9	1.872	1.867	0.267

Table 2.3 ANN model assessment with confidence level of 95% using p-value

Runs	p-value ANN reproduction
Mean duo of test-t	0.721
Variance in test-F	0.799

3. Result

3.1 Analysing Surface Roughness

Surface roughness is one of the most crucial parameters in defining how a physical component will interact with itself and/or its surroundings. Rough surfaces often have a greater friction coefficient and wear more quickly upon contact than smooth surfaces in tribology (Svahnet al., 2003). Engineering materials' rough surfaces are recognized to have a negative impact on part performance. Even though it's normally undesirable, having a high roughness value, controlling it in manufacturing can be challenging and costly. Lowering the roughness value frequently results in higher production costs. In this study, the sample is divided into three parts and average of their roughness was taken, the lowest surface roughness region was reached under hybrid cooling conditions and only one insert was sufficient to cut the all the samples. Fig 6 is the SEM image of the tool insert after cutting all the samples. In this sense, employing the appropriate cooling strategy can significantly reduce tool wear. (Gupta et al., 2023). It has been discovered, therefore, that lubrication and cooling both serve to enhance the workpiece's quality of finish.

3.2 Taguchi Method

To determine any differences between experimental and goal values, Taguchi is utilized. It employs the S/N ratio, to indicate the response's mean value and standard deviation, respectively (Ezugwu et al., 2005). Signal-to-noise (S/N) ratio was computed for every input level. Using base 10 log, the smaller-is-better S/N ratio formula used was:

$$S/N = -10*\log(\Sigma(Y2)/n) \quad (1)$$

where Y denotes the responses for the specified factor level combination and n denotes the total number of responses for the combination of factors. This study employs the *S/N* ratio of the quality characteristic to minimize the surface roughness, and this is often the selected S/N ratio for all undesired attributes (e.g., "defects, tool chatter," etc.), where zero is the best value. The quality description including surface roughness Ra is found through optimization using the smaller-the-better characterization method in the current experiment. To determine S/N ratios, reflect the smaller the better attributes equation. Therefore, the S/N ratio was calculated using equation (1), and the results are displayed in table 4, additionally, it demonstrates that feed is ranked as one and has a major impact on the process.

Table 4. S/N Ratios for Ra

Level	s (m/min) A	f (mm/rev) B	d (mm) C	Rice Bran oil(ml/min) D
1	-2.449	-1.947	-2.845	-3.831
2	-3.185	-2.349	-2.753	-3.047
3	-3.159	-4.497	-3.195	-1.915
Delta	0.736	2.550	0.442	1.916
Rank	3	1	4	2

Similarly, the average analysis of every study variable is shown in the response plot for means. Response Means test variations, which have been refined at each level by the Taguchi technique, are displayed in Table 5 which also shows that the average ratio for each variation of the speed feed, doc and rice bran oil on the surface roughness. The reaction yields result by averaging each level fluctuation, which yields an average difference.

The Delta describes three parameters and their respective magnitudes of effect. It can be depicted from Tables 4 and 5 that for Ra, feed has a significant impact on the machining process, followed by rice bran oil.

Table 5. Table of Responses for Means

Level	s (m/min) A	f (mm/rev) B	d (mm) C	Rice Bran oil(ml/min) D
1	1.329	1.255	1.406	1.572
2	1.467	1.320	1.409	1.436
3	1.466	1.687	1.447	1.255
Delta	0.138	0.432	0.041	0.317
Rank	3	1	4	2

3.3 Process parameter effects on performance attributes.

3.3.1 Effects of process inputs on Ra

Fig.2 and 3 shows the results of Ra's input parameters. With the optimum cutting speed, Ra was seen to be declining. This is caused by increased temperature in the machining zone brought on by friction amid the material of the work piece and the tool. Additionally, more rapid cuts cause the material to soften, resulting in the lowest possible surface roughness. As observed in Fig.3, the Ra value decreases when the ideal machining settings are applied, and the Ra value increases with elevated levels of feed parameters. So, the key findings are the use of rice bran oil as a cutting fluid at 150 ml/min the Ra value was found to be optimum for machining. Fig.4 and 5 confirms the same. The present study's surface roughness trends with rising feed rate, depth of cut, and cutting speed, respectively, concurred with previous research findings about material machining. As seen in Fig. 2, the kind of coolant atmosphere has a major impact on Ra. Small Ra was found when rice bran oil was combined with an Al_2O_3 cutting environment. This is when pouring rice bran and Al_2O_3 cutting fluid at the machining zone results in lower cutting region temperatures, which reduce detritus on the machined face while decreasing surface roughness.

3.3.2 Determining ideal cutting parameters for Ra.

Table 4 displays the S/N ratio response table that was produced for the Ra. The graph of mean S/N ratio generated using the Minitab software is shown in Fig. 3. A higher S/N ratio indicates the least amount of fluctuation between the measured and desired outputs. It can be shown from Fig. 3 that the maximum mean S/N ratio for Ra was achieved at 102 rpm for cutting speed, 0.1 mm/rev for feed rate, 0.4 mm for cut depth, and 150 ml/min for rice bran coolant, in that arrangement. Consequently, it was determined that the following process variables would yield the lowest surface roughness when utilizing the Taguchi method: v = 102 rpm, f = 0.1 mm/rev, d = 0.4 mm, with 120 (ml/min) rice bran oil as coolant.

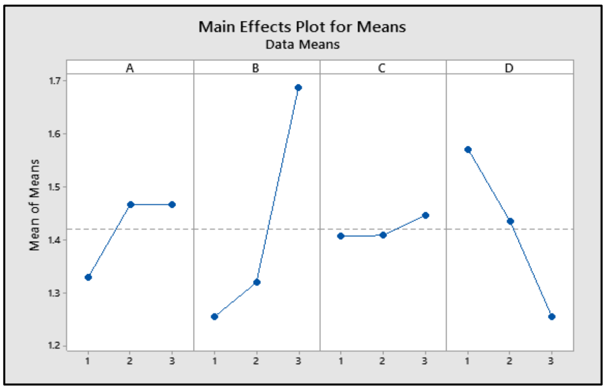

Figure 2. Ra's S/N ratio mean plot

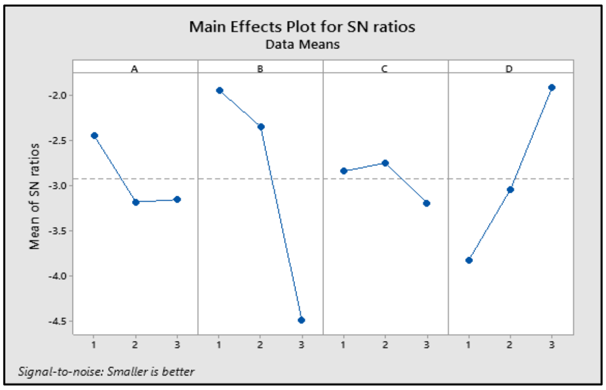

Figure 3. Ra's S/N ratio plot

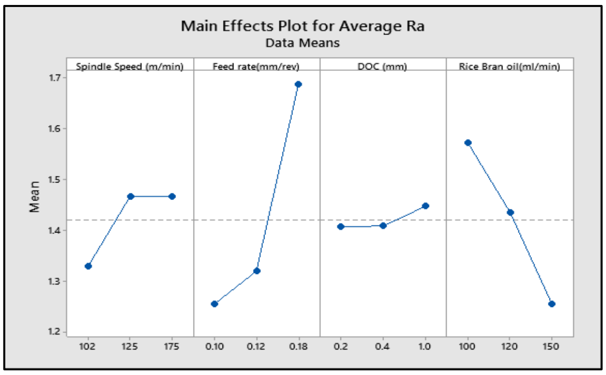

Figure 4. Ra's main average plot

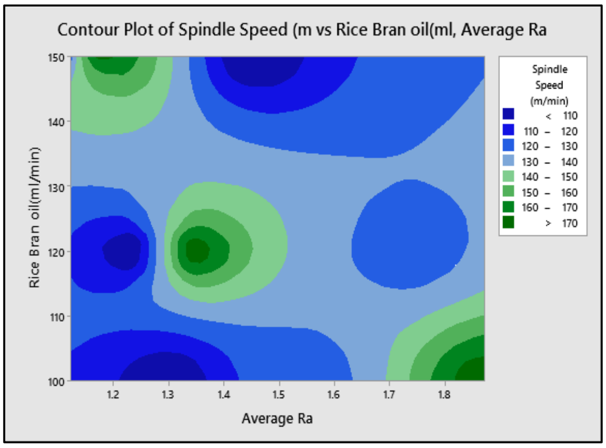

Figure 5. Ra's contour average plot

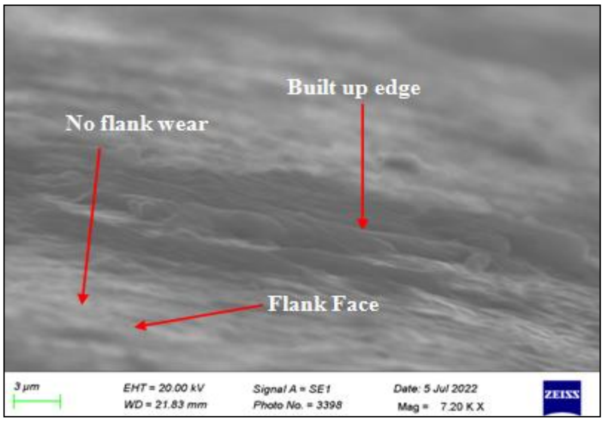

Figure 6. SEM image of tool insert TiAlN

The machining of the material is difficult and in this case, we have used TiAlN along with rice bran oil as coolant. An ideal depth of cut of 1.0 mm is advised based on the figure since it was seen that a rising trend was achieved for the surface roughness value as the depth of cut increased. Fig.7 and 8 are the snapshots taken at the actual working site.

Figure 7. Specimen of 17-4PH

Figure 8. Specimen of 17-4PH

3.3 Oil based Cutting

MQL (rice bran oil) is known to perform better than MQL (coconut oil). Comparing MQL (rice bran oil) with dry as well as MQL (coconut oil) machining, the former shows superior machined surface texture, lesser tool wearout, reduced tool-tip temperature, as well as decreased cutting force (Chandrakant et al., 2023). The oil made from rice bran Fig. 9 a and b had the lowest coefficient of friction; as a result, less machining effort was required due to the reduced friction force. Additionally, it is evident that rice bran oil has the most excellent surface, which further supports its status as the superior lubricant.

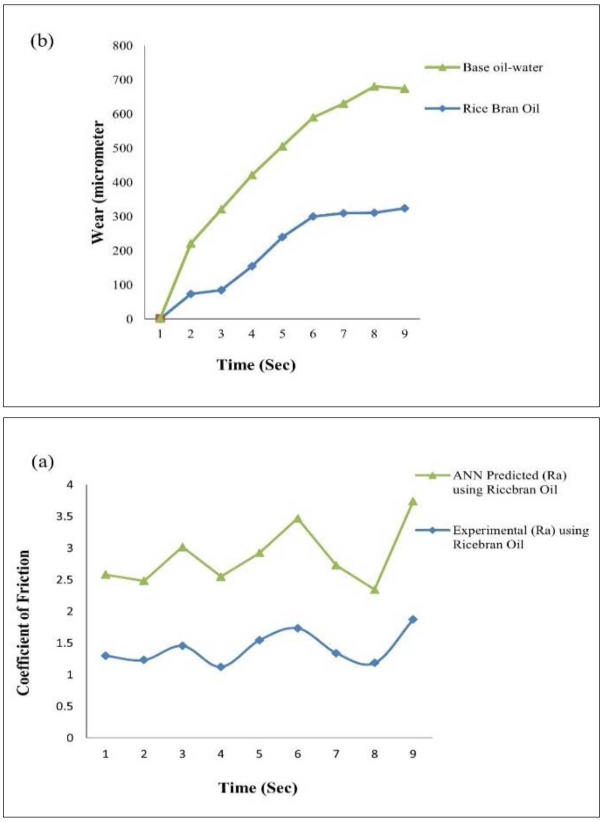

Figure 9. Wear of Material (a) fluctuations in the coefficient of friction (b) time

3.4 Test for Confirmation

There are various benefits of using MQL for machining as opposed to conventional dry machining. The properties of the cutting fluid are crucial for the effectiveness of the machining process. The results of the confirmation tests are presented in Table 6, and these findings suggest that the parameters selected are reasonably close to both the test results and the expected results.

Table 6. Conformation tests of obtained results

s (mm/rev)	f (mm)	d	Rice oil(ml/min)(m/min)	Bran (Ra)
102	0.12	0.4	120	1.231
102	0.12	0.4	120	1.231
102	0.12	0.4	120	1.231

4. Conclusions

17-4 PH steel was processed in a coolant that was made by combining rice bran oil with Al_2O_3, and the surface quality was examined to determine the work piece's machinability in these coolant conditions and following conclusions were drawn:

- The surface imperfections that define the surface quality are heavily influenced by the cutting environment. It is evident from the results that using rice bran and Al_2O_3 as coolant produced improved surface quality.
- Ra was mostly dependent on feed rate and rice bran oil with the respective percentage contributions of 58.06% and 49.5%.
- Based on the findings, it was noticed that the ideal machining conditions identified by Taguchi considerably decreased the surface roughness when 17-4 PH was being machined. Therefore, it can be advised that metal-cutting industries make use of these ideal cutting conditions to increase 17-4 PH's machinability within the specified range.
- The expected response results and the experimental results showed a strong agreement for the created mathematical models for Ra. Therefore, it would not be necessary to perform trail experiments on materials that are challenging to cut in order to evaluate product quality using the suggested models for appropriate cutting condition selection.

- The experiment's goal was to create items with sustainable manufacturing, and tables 4 and 5 show that it was successful because rice bran oil greatly reduced the frictional forces generated during the manufacturing process.
- An ideal depth of cut of 1.0 mm is advised based on the figure since it was seen that a rising trend was achieved for the surface roughness value as the depth of cut increased.
- The third trial is most suitable for achieving the experiment's goals.
- The input and output were modelled using the ANN toolbox in the MATLAB program. The research shows the predicted and optimal outcomes are in close proximity.

5. Restraints and Future Activities

Following are the study's limitations and recommendations for further study.

- The current work exclusively compares the outcomes under these cooling circumstances, and the cutting experiment parameters are maintained constant.
- The chips discharged during cutting and the oil mist that accumulates in the cooling environment have an effect on the measurement's precision.
- The entire energy consumption can be determined by factoring in the energy expenditure of external sources, such as compressors and MQL devices.
- Additionally, the coolant was exceedingly difficult to combine with the Al_2O_3 and had little impact on the MQL oil's viscosity.

The following is a list of suggestions regarding the direction of future research:

- Understanding the process and making the data easier to comprehend may be facilitated by the numerical amplification of the experiment result through the proposal of suitable numerical models.
- The work piece's effects from the hybrid cutting environment, both mechanical and thermal, can be explored in subsequent studies.
- The impact of cooling techniques on wear on tools and the surface's integrity can be investigated in the machining of such materials produced through machining.
- Based on the study's findings, more research can be done in the field of process parameter optimization, post-processing treatment application, and machined component uniformity. More specifically, there is the potential to improve the mechanical property performance in comparison to the sample through investigations into reducing porosity via coolant flow rate adjustments and machining techniques that significantly minimize cutting forces.
- Testing the lubricating and cooling conditions via tribology is possible.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

Vivek John: Conceptualization, Writing - review and editing, Supervision; Dr. Vinny John and Vivek John; Resources, Experimentation, Writing - original draft preparation; Dr. Vinny John: Writing - review and editing. All the authors read and approved the manuscript.

Ethical approval statement

Ethical approval is not applicable for this research.

Abbreviations and acronyms

Spindle speed – s, Feed – f, Depth of cut – d, Surface roughness –Ra, Rice bran oil - RBO

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