DOI:https://doi.org/10.52756/ijerr.2024.v38.006 *Int. J. Exp. Res. Rev.*, Vol. 38: 61-68(2024)

Original Article | Peer Reviewed | Open Access

International Journal of Experimental Research and Review (IJERR)
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ISSN: 2455-4855 (Online)
www.iaph.in

Orthogonal array and artificial neural network approach for sustainable cutting optimization machining of 17-4 PH steel under CNC wet turning operations

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Article History:

Received: 18th Jul., 2023
Accepted: 13th Mar., 2024
Published: 30th Apr., 2024

Keywords:
Orthogonal array, artificial neural network approach, sustainable cutting optimization machining, 17-4 PH steel, CNC Wet Turning operations.

How to cite this Article:
Vivek John, Saurabh Aggarwal, Deepak Gupta, Harishchander Anandaram and Kapil Joshi (2024). Orthogonal array and artificial neural network approach for sustainable cutting optimization machining of 17-4 PH steel under CNC Wet Turning operations. *International Journal of Experimental Research and Review*, *38*, 61-68.
DOI:https://doi.org/10.52756/ijerr.2024.v38.006

Abstract: Sustainable manufacturing strives to increase output while minimizing resource usage, costs, and environmental impact. Tool longevity is crucial, considering material, power, and resource consumption. Challenges like chip removal, heat, and friction necessitate effective solutions. Cutting fluids, like rice bran oil, reduce temperatures, friction, and enhance tool life and surface quality. Research focuses on using rice bran oil with a TiAlN tipped tool to minimize friction and cutting forces. Taguchi's robust design and L-9 orthogonal array reduce experimental trials. Controllable factors include speed, feed, depth of cut, and rice bran oil flow rate, with surface roughness as the performance metric. Taguchi analysis improves turning performance, particularly with 17-4 PH stainless steel. Rice bran oil reduces frictional forces, enabling improved surface quality across all samples, promoting sustainability. Surface roughness (Ra) is notably influenced by feed rate and rice bran oil, contributing 58.06% and 49.5%, respectively. This research underscores the potential of optimizing cutting fluid and process parameters to enhance sustainability in manufacturing.

Introduction

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 boric acid 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 characteristics and structural makeup of 17-4PH make machining challenging and lubricants necessary (Venkatalaxmi et al., 2004). In this situation, the tool tips (Warcholinski et al.,

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Table 2. Experiment and Forecasted standards of surface roughness using ANN.

Sample No.	Surface Roughness (µm) Experimental	Surface Roughness (µm) ANN	Error (%)
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

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 between the chip and the tooltip significantly decreases during machining when LN2 is sprayed (Hong et al., 2001). Researchers have only somewhat investigated the metal-cutting ability of 17-4 PH base metal procedures(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, which 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).

Here, 70 mm long and 40 mm diameter of 17-4 PH Steel were used in the current study. The orthogonal L9 array, proposed by Taguchi, was used to evaluate the test piece under three different extents speed, feed and depth of cut. It is a robust design tool that makes use of orthogonal arrays, which can handle multiple design aspects at onceand S/N ratio, which assesses features with highlighting on variance, to provide an easy and systematic way to optimize plans for performance, quality and associated cost. Taguchi orthogonal arrays are used to design experiments. 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. Turning operations were carried out using carbide-tipped tools with a positive and negative rake angle (Elangovan et al., 2010; Krolczyk et al., 2015). Comparing the data showed 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 best cutting parametric combination for achi- eving low surface roughness, and it was established

Table 1. Details of an experimental trial.

Spindle Speed (m/min)	Feed Rate(mm/ rev)	Depth of Cut (mm)	Rice Bran oil(ml/min)	Average Surface Roughness (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

that this combination resulted in a 52.6 percent fall in surface roughness.

According to a literature review, there is little 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.

Methodology

ANN Model Influencing Factors

Researchers frequently employ ANN for modelling purposes in various fields, including machining (Li et al., 2018; G, V. and M. D., 2023; Haloi et al., 2023). The surface roughness of 17-4PH steel has been predicted using ANN modelling in this work. The ANN parameters were chosen using 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 displays the data set's predicted outcomes. As can be observed, the neural network forecast generally falls pretty near the investigational value.

Table 3. ANN model assessment with a confidence level of 95% using p-value (surface roughness).

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

Table 4. S/N Ratios for Ra.

Level	Speed (m/min) A	Feed (mm/rev) B	DoC (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

Table 5. Table of Responses for Means.

Level	Speed (m/min) A	Feed (mm/rev) B	DoC (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

The outcomes of the turning operation are compared using a created mathematical model. So, the obtained models might be applied to machining selection to evaluate the quality of the results. The best machining parameters show that feed and rice bran oil were the most important machining parameters for low surface roughness, 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 prominence on variance to provide an easy and efficient move towards design optimization for performance, quality, and associated cost (Choi et al., 2019). The experimental work was performed at Uttaranchal University's Mechanical Engineering Department.

Results

Taguchi Method

Taguchi is utilized to determine any differences between experimental and goal values. It employs the S/N ratio to indicate the response's mean value and standard deviation (Ezugwu et al., 2005). 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. It is evident from Tables 4 and 5 that for Ra, feed has a significant impact on the machining process, followed by rice bran oil.

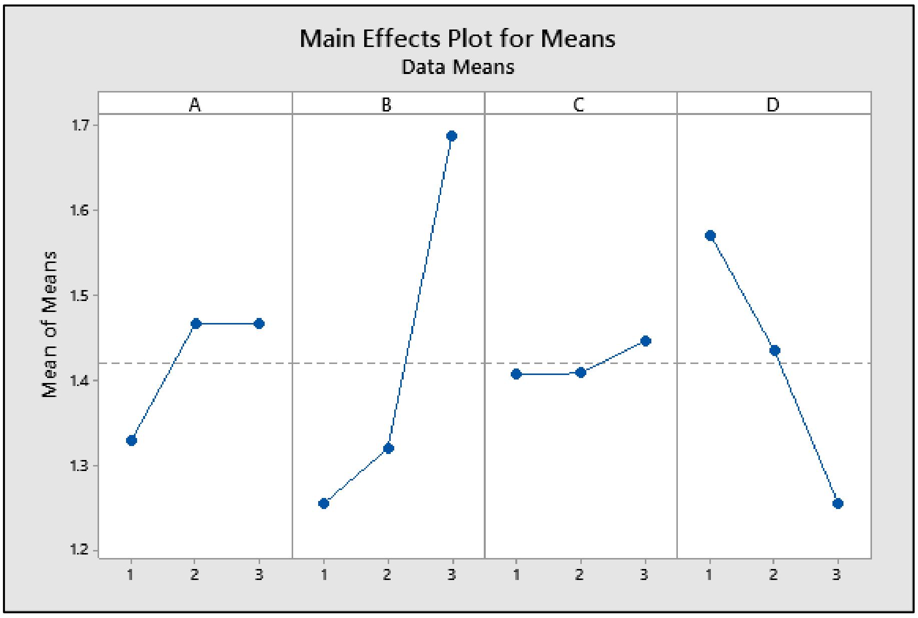

Figure 1. Ra's S/N ratio mean plot.

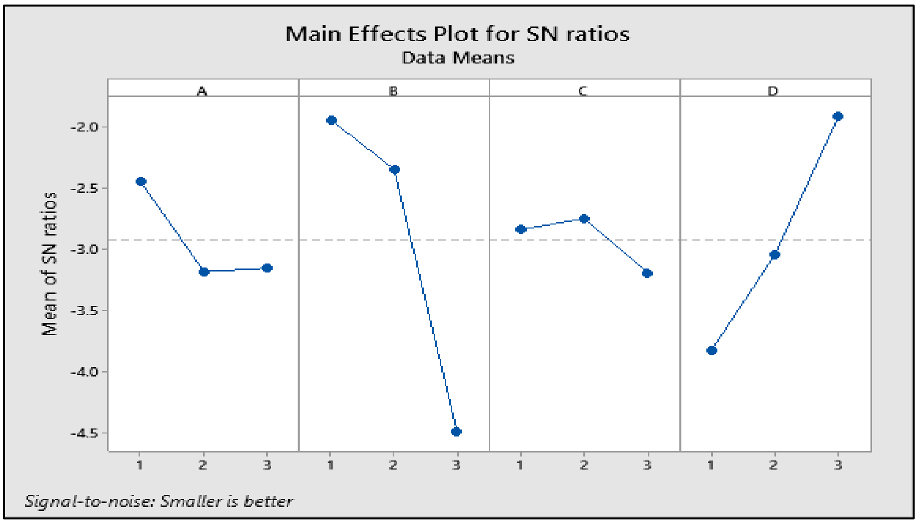

Figure 2. Ra's S/N ratio plot.

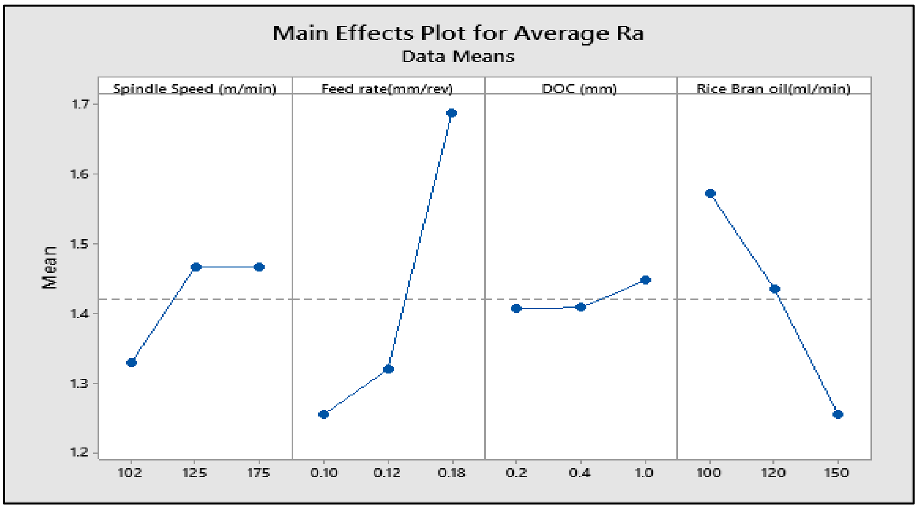

Figure 3. Ra's main average plot.

DOI:https://doi.org/10.52756/ijerr.2024.v38.006

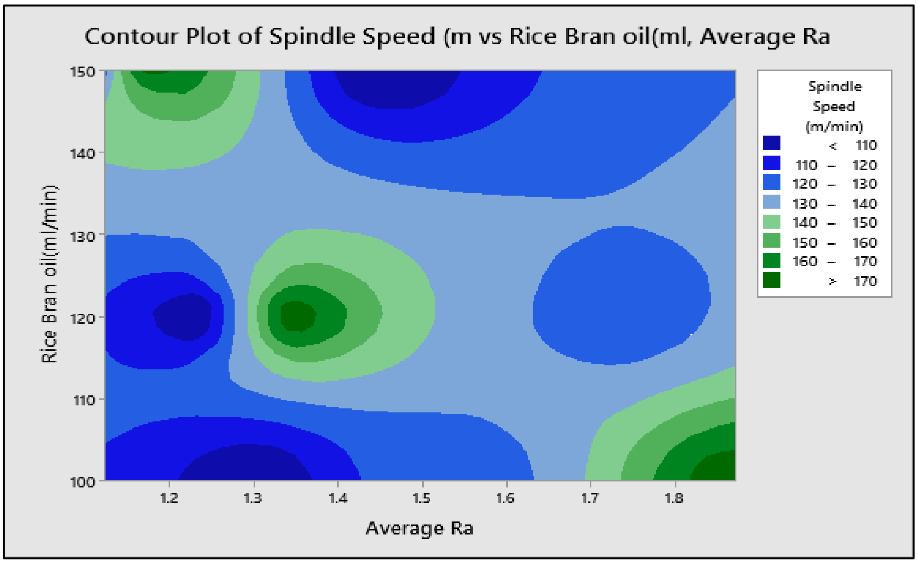

Figure 4. Ra's contour average plot.

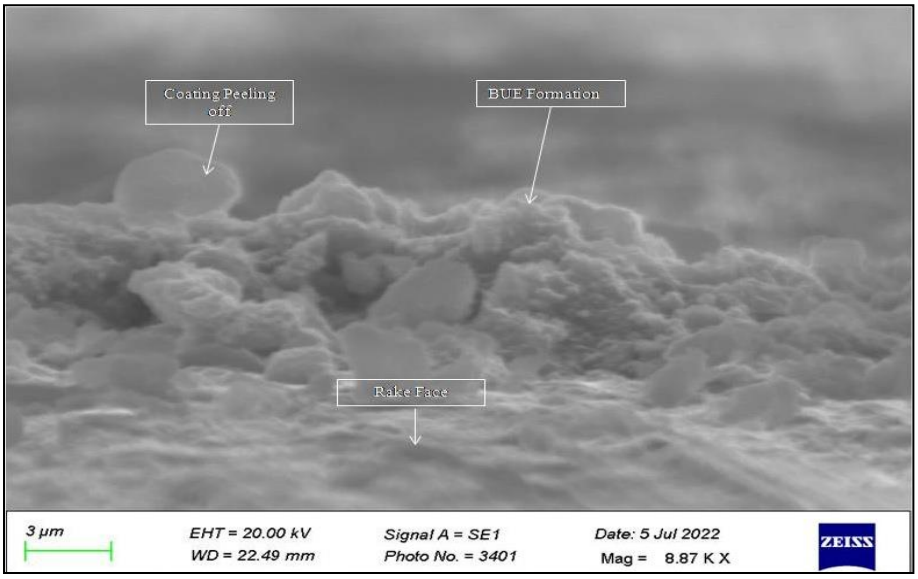

Figure 5. SEM image of tool insert TiAlN.

Figure 6. Specimen of 17-4PH.

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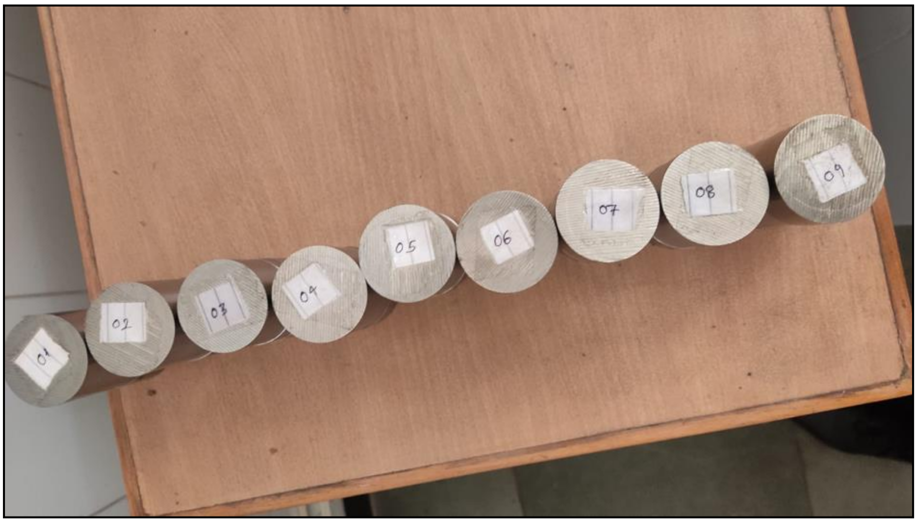

Figure 7. Specimen of 17-4PH.

Figures 1 and 2 show the results of Ra's input parameters. With the best cutting speed, Ra was seen to be declining. This is caused by increased temperature in the machining zone brought on by friction between 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 Figure 2, 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 finding is the use of rice bran oil as a cutting fluid at 150 ml/min. The Ra value was found to be optimum for machining. Figure 3 and 4 confirm the same.

The machining of the material is difficult; in this case, we used TiAlN and rice bran oil to cut the fluid. 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. Figure 6 and 7 are the snapshots taken at the actual working site.

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. Ra was mostly dependent on feed rate and rice bran oil, with respective percentage contributions of 58.06% and 49.5. 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 experiment was designed using the L9 orthogonal array. It produced minimal surface roughness and flank wear when machining such strong material, making it more appropriate for aerospace, chemical, and marine applications. The input variables v, f, and d substantially affect machining. The third trial is most suitable for achieving the experiment's goals. The ANN toolbox in MATLAB software was used to model the input and output. The research shows the predicted and optimal outcomes are in close proximity.

Table 6. Conformation tests of obtained results.

Speed (m/min)	Feed (mm/rev)	DoC (mm)	Rice Bran oil (ml/min)	Average Surface Roughness (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

Test for Confirmation

The results of the confirmation tests are presented in Table 6, and it can be inferred from these results that the test results and the projected results are fairly close to the parameters chosen.

Acknowledgement

This research has been done under the seed money project. We are very thankful to Uttaranchal University for accepting our proposal and providing funding to complete the research work. We are also thankful to the

Head, Mr. Sanjeev Kumar Joshi of the Mechanical Engineering Department, Uttaranchal University, for allowing us to use CNC Lathe machine to conduct the experiments.

Conflict of Interest

The authors disclose no conflicts of interest.

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How to cite this Article:
Vivek John, Saurabh Aggarwal, Deepak Gupta, Harishchander Anandaram and Kapil Joshi (2024). Orthogonal array and artificial neural network approach for sustainable cutting optimization machining of 17-4 PH steel under CNC wet turning operations**.** *International Journal of Experimental Research and Review*, *38,* 61-68.
DOI:https://doi.org/10.52756/ijerr.2024.v38.006