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Sustainability Issues in Turning Process: A Study in Indian Machining Industry

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Abstract

Manufacturing industries are crucial in a country's economy. However, they account for huge resource consumption and waste excretion. The objective of this study was to investigate sustainability issues pertinent to turning process in a Indian machining industry. Parameters such as surface roughness, material removal rate and energy consumption were considered as sustainability factors. The effect of process parameters (speed/feed/depth of cut), the machining environment (dry/MQL/wet) and the type of cutting tool on the response was observed. Analysis of Variance (ANOVA) was applied to test the data. The process was analysed using response surface methodology (RSM). The results of the study helped to understand the effect of the cutting parameters on surface finish, energy consumption, and material removal rate. The process was optimized from power consumption point of view. Extended form of the model could be useful to predict the environmental impact of machining process which will bring environmental concern into conventional machining.

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Nomenclature

V_c	Cutting Speed
a	Depth of cut
f	Feed
I_L	Line Current
V_L	Line Voltage
MRR	Material Removal Rate
Env	Machining Environment
MQL	Minimum Quantity Lubrication
P	Power required for Machining
RSM	Response Surface Methodology
Ra	Surface Roughness
Tt	Tool Type

1. Introduction

In the recent years, manufacturing industry is exploring sustainable product development through sustainable manufacturing. This shift is a result of increased awareness among the manufacturer and the users [1]. All countries are being compelled to reduce negative environmental impact of manufacturing process. The environmental concern and focus is above the interest of any individual, organization or country. For a better and safe environment we must not compromise. [2] Machining industry is the most energy consuming and waste generating industry. The major question is how to use a manufacturing process so that the emissions will be on lower side and will provide high productivity. [3]. Sustainability is no longer a choice now rather it has become a need of today.

Various methodologies are adopted by researchers to understand the sustainability of a machining process. A three dimensional system approach by Yuan et al. [4] highlighted sustainability issues of manufacturing from pollution prevention point of view. Three key components of process namely technology, energy and material were considered for the study. Supported case study shows the effective use of methodology in a nano-scale manufacturing unit. Li et al. [5] presented eco efficiency approach for evaluating energy consumption as well as the resource utilization in manufacturing process supported by a case study of grinding process. Munoz and Sheng [6] focused on waste streams of machining process considering process mechanics, tool wear, metal working fluid loss, chip waste and energy consumption. Jiang et al. [7] described a new method for environmental assessment of manufacturing process for entire process plan. The weights for process plan parameters were obtained using Analytical hierarchy processing (AHP) approach.

Life cycle Assessment (LCA) is widely considered for understanding the environmental impact of a manufacturing process. It is an authoritative instrument to analyze the manufacturing process. Narita et al. [8] developed a methodology to assess environmental burden of a machining process using LCA methodology. The model developed provides equivalent CO₂ for the process using the energy consumption, metal working fluid used, chip generated and tool used in the process. Branker et al. [9] presented new economic model based on LCA methodology. Theoretical and experimental results were used to validate the model for carbon emission and cost sensitivity. Use of LCA methodology demands the knowledge of LCA study. Many of the industries may not have recourses available for the same. Also the availability of environmental data of the country is a major concern.

Large numbers of parameters namely economic, environmental and social need to be evaluated for sustainability assessment of a machining process [10,11]. In any analysis it is important to define the boundary of the study first [12]. Multi criteria decision making approaches like Analytical hierarchy Processing (AHP), Analytical Network processing (ANP), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) etc can be applied for the assessment. The outcome of such analysis would be based on the judgment of the decision maker which no doubt depends on his / her experience and knowledge.

The issues in Indian Machining industry are slightly different than the other developed countries. Because of profound availability of skilled manpower, conventional machining is still being used by large. Majority of workers in such small scale industry lacks proper training and hence it is very difficult to make them understand the concepts of mathematical model and outcomes. While Most of the methods are being developed and applied for CNC machining, sustainability assessment of a conventional machining process at small scale industry is rarely focussed. . Thus, there is a need of developing a simple model which will be easy to understand and can be easily incorporated in small scale industries working on conventional machining [12]. Motivated by this problem paper discusses

sustainability issues in a conventional machining process.

Process parameter and cutting environment plays important role in a machining process. An economic and environmental impact aspect of machining highly depends on these parameters. Muthukrishnan and Davim [14] studied effect of machining parameters on surface roughness of Al-SiC using coarse grade Polycrystalline diamond (PCD) inserts. Artificial Neural Network (ANN) and Analysis of Variance (ANOVA) was used to validate the results. Rajemi et al [15] developed a model for optimizing energy footprint of machined product. They identified critical parameters in minimizing energy use and hence reducing energy cost and environmental impact.

The sustainability issues presented in this paper emphasises on economic and environmental aspect of machining process based on energy use, material removal rate, and surface finish of product manufactured. Here an attempt has been made to avoid complexity in the model which will allow any person working in the conventional machining industry to understand the process impacts easily.

2. Selection of Input and Output Parameters

The model is targeted for the small scale industries therefore it is necessary to keep the Input/ Output parameters to minimum to avoid complexity. It was necessary to find out the most influencing process parameters in machining. The literature review suggested that major influencing parameters in a machining process are work piece material, cutting environment (Dry / Wet / MQL), type of Tool, and the process parameters i.e. cutting speed, feed & depth of cut. But all the mentioned factors are hardly considered together for the study. The output parameters for the purpose of sustainability can be too many. In this paper, three important output parameters namely surface roughness, material removal rate and power consumption are considered.

3. Material and Method

3.1 Experimental Conditions

Three machines in different industries were selected to accomplish the experimentation work and gather the data. Different skills and education level workers were chosen for absorbing variation in the process modeling. Experimentation was performed on three conventional medium duty lathe machines with varying capacity and motor power. AISI 1040 carbon steel commonly known as EN-8 was selected for the case study because of its wide engineering applications. Three types of tools namely Brazed ceramic tool, Insert with Titanium Nitride (TiN) Coating and Insert with Titanium Aluminum Nitride (TiAlN) coating, which are most commonly used in machining industry are selected for study purpose. The details are listed in table 1. The geometry of the component was kept constant throughout experimentation.

Experimental design is widely used in many engineering applications. If there are number of influencing factors the fractional factorial design is more effective. In factorial design, as number of input parameters increases the experiment to be conducted rapidly increases. L₂₇ orthogonal array is a systematic and effective method which provides better results with reduced number of experiments

when all factors are considered at three level. To compensate for the measurement errors each experiment is being replicated three times and average value of variable is considered for experimentation and analysis. Table 1 shows details of the machine, cutting tool, tool holder and cutting fluid used during the experimentation. The input parameters were varied at three levels. The variable values at various levels used during experimentation are listed in table 2. The experiments were carried out in accordance with 3 level L27 orthogonal array using design of experiment technique.

Table 1 : Details of the machine, tool , tool holder and cutting fluid

SN	Particular	1	2	3
1	Lathe Motor Power	1.5 HP	2.0 HP	3.0 HP
2	Cutting Tool Insert	CNMG 120412 TF (AlTiN coated) CNMG 120412 MP (TiN coated)		
3	Tool Holder	PCLNR/L 1616H 12-M SANDVIK		
4	Cutting fluid	Servocut-S (Manufactured by Indian Oil)		
5	Cutting Fluid flow rate (Wet)	5 % cutting fluid mixed with water and flow rate of 15 lit /hr.		
6	Compressor Air Pressure (MQL)	Air at 4 bar & 5% cutting fluid mixed with water & cutting fluid flow rate of 90 ml/hr.		

Table 2 : Machining parameters

SN	Parameter	Level 1	Level 2	Level 3
1	Cutting Speed (m/min)	21.93	33.73	50.55
2	Feed (mm/rev)	0.1658	0.1855	0.2107
3	Depth of Cut (mm)	0.5	0.75	1.0
4	Environment	Dry	MQL	Wet
5	Tool	Brazed tip	TiN coated Insert	TiAlN coated Insert

Table 3 : Material Composition of AISI 1040 (EN-8)

C %	Si %	Mn %	S %	P %	Cr %	Mo %	Ni %
0.36	0.10	0.60	0.05	0.05	-	-	-
0.44	0.40	1.00	max	max	-	-	-

Table 3 shows the material composition of AISI 1040 used for the study

3.2 Experimental procedure and measurements

The work piece as per geometry as shown in figure 1 was provided to the worker. All the machines selected were having four spindle speeds available for use. The most suited and used speeds were selected for the experimentation. The depth of cut was selected as 0.5 mm, 0.75 mm and 1 mm. The worker was allowed to choose feed by their experience. They were asked to vary the feed as slow, medium and fast. Since the experimentation was carried out as a manual operation there was variation in the feed hence we decided to perform three replicates of each experiment and take average value to minimize the measurement errors. The orthogonal array L 27 was followed for the experimentation. The experimentation was carried out in three shifts i.e. Morning, afternoon and evening.

The raw work piece material of 30 mm diameter was cut into pieces of 43 mm length. All the pieces were weighed with the help of weighing scale and the dimensions were

measured using digital Vernier caliper. This was necessary to find the amount of material removed during the machining accurately as it could be difficult to collect and measure the weight of the chips produced during operation. Each raw work piece was coded to facilitate the after analysis of finished product. To determine the spindle speed non contact tachometer was used. To maintain constant flow rate of the cutting fluid coolant pump was set to deliver flow rate of 15 lit / hour. The flow rate was selected based on worker experience and was maintained constant throughout experimentation. To deliver air and cutting fluid mixture during minimal quantity lubrication condition spray gun and the compressor was used with a coolant flow rate of 90 ml /hr at 4 bar air pressure. The variation in current during operation and idle running was measured using the clamp meter and Power required was calculated using eq 1, where $\cos \phi$ represents power factor value. Lathe motor being inductive load, in this study it is considered as 0.7. The power consumed by the coolant pump during wet machining was also measured in the same way. The Power required by the compressor was measured for the amount of time the compressor was switched on for compressing the air. It was observed that the total cycle time of charging and discharging was approximately 34 minutes. Out of that the compressor was using the electricity for 5 minutes to get the required air pressure. Once the pressure was reached to 6 bar the power supply was cut off. The amount of electricity used during this cycle was distributed over the machining time of the work piece and added in total power consumption.

$$P = \sqrt{3} V_L * I_L * \cos \phi \quad (1)$$

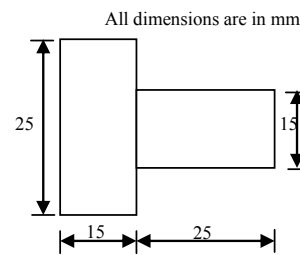


Fig. 1: Work piece geometry



Fig. 2 : Handy surf E35 B Surface roughness tester



Fig. 3: Finished work piece samples

The surface roughness of the machined component was measured using Handy-surf E35-B surface roughness tester shown in Fig. 2 with a cut-off length of 0.8 mm and sampling length 5 mm. Average surface roughness(Ra) was calculated by taking average of three readings obtained at three

different points of machined surface. After machining was over the finished component was measured for dimensional accuracy and weighed to determine the amount of material removed. The tolerance for dimensional accuracy was maintained at ± 0.05 mm. It could have been difficult to measure timings accurately during the process hence we decided to take video shooting of all experiments for later analysis.

3.3 Data Analysis

The experimentation was conducted on three machines to compensate for variation in data. Data was collected for 27 experiments with three replications on each machine. We recorded 243 data samples in all. For analysis purpose the similar experimental conditions on all machines were grouped and average value of input / output variable was used for the analysis. The data was analyzed using Minitab 16 software. This software provides excellent tools for statistical analysis of the data. MS-Excel was also used for calculation and plotting. Fig 3 depicts the finished components obtained from the experimentation.

4. Results and Discussion

4.1 Taguchi analysis

The purpose of the study was to investigate factors influencing sustainability issues in machining industries. The Taguchi analysis was performed using Minitab 16 software to understand the influencing parameters on responses.

Table 4 : Response Table for Signal to Noise Ratios for Surface Roughness (Smaller is better)

Level	Environment	Tool type	Cutting speed	Feed	Depth of cut
1	-14.08	-15.56	-13.48	-12.82	-12.61
2	-11.29	-11.03	-12.86	-12.12	-12.40
3	-12.57	-11.33	-11.59	-12.99	-12.93
Delta	2.79	4.53	1.88	0.87	0.53
Rank	2	1	3	4	5

Table 5 : Response Table for Signal to Noise Ratios for Material Removal Rate (Larger is better)

Level	Environment	Tool type	Cutting speed	Feed	Depth of cut
1	30.61	29.93	30.21	30.04	29.84
2	30.46	31.52	30.24	30.84	31.33
3	31.67	31.29	32.29	31.86	31.57
Delta	1.20	1.59	2.08	1.82	1.73
Rank	5	4	1	2	3

Table 6 : Response Table for Signal to Noise Ratios for Power required for machining (Smaller is better)

Level	Environment	Tool type	Cutting speed	Feed	Depth of cut
1	35.54	28.78	28.95	29.27	28.93
2	24.81	30.25	29.60	29.52	30.31
3	28.89	30.22	30.69	30.45	30.00
Delta	10.73	1.47	1.74	1.18	1.38
Rank	1	3	2	5	4

Table 4 shows the results for signal to noise ratio of surface roughness (Ra) verses the input parameters. Smaller is better criteria was selected for analysis. The ranking depict that tool type, machining environment and cutting speed are ranked 1, 2 & 3 as influencing parameters on surface finish.

Table 5 suggests that material removal rate (MRR) depends on cutting speed, feed and depth of cut while tool type and machining environment also contributes to certain extent. Table 6 shows the signal to noise ratio for power required for machining (P). Cutting environment is significant parameter for power consumption compared to rest as during wet conditions the pump power and during MQL condition the compressor power is added while calculating total power. The S/N ratio shows close relationship of the Input parameters on the responses.

4.2 Response Surface Method

In this study all the variables are quantifiable hence we decided to use response surface methodology which is a statistical technique to analyze a number of independent variables influencing the response [16]. Response Surface Methodology (RSM) is a set of techniques used in the empirical study of relationships between one or more responses and a group of variables (Cornell, 1990). In RSM second order polynomial equation used to represent response Y is given as eq. 2

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \quad (2)$$

Here, the polynomial is being developed for five influencing variables on responses Ra, MRR and P.

4.2.1 RSM model for surface roughness Ra

Table 7 shows the ANOVA results of the model. The data was provided in coded form for input variables. The ‘p – value’ in the last column represents the influence of the of the terms. For 95% confidence level the p-value less than 0.05 we reject the null hypothesis that parameter does not affect the response in other words it indicates significant influence of the parameter.

Table 7: Analysis of Variance results for Surface Roughness Ra (Significant terms Only)

Source	DF	Seq SS	Adj SS	Adj MS	F	p
Regression	17	69.5398	69.5398	4.0906	7.78	0.002
Linear	5	41.0942	29.5827	5.9165	11.26	0.001
Env	1	4.2018	10.4528	10.452	19.89	0.002
Tt	1	28.9701	12.0953	12.095	23.02	0.001
Square	5	22.6427	23.1037	4.6207	8.79	0.003
Env * Env	1	9.2192	9.2192	9.2192	17.55	0.002
Tt * Tt	1	11.8994	11.8994	11.899	22.65	0.001
f*a	1	0.4241	0.4241	0.4241	0.81	0.392
Residual Error	9	4.7291	4.7291	0.5255		
Total	26	74.2689				
Std. Deviation		0.72488		R-Sq =		93.63%
Press		50.0944		R-Sq(adj) =		81.60%

Lower p value of the regression model shows that the model is significant. It can be inferred from table 7 that machining Environment and Type of tool influences the surface roughness while feed contributes to certain extent. Eq. 3 represents the RSM model for surface roughness (Ra). The

values $R^2 = 93.63\%$ and $R^2(\text{adj}) = 82\%$ obtained for model indicates high significance of the model.

$$\begin{aligned} \text{Surface Roughness (Ra)} = & 24.2191 - 7.7294\text{Env} - 7.8198\text{Tt} \\ & + 1.1085\text{Vc} - 3.4217\text{f} - 1.7592\text{a} + 1.2396\text{Env}^2 + 1.4083\text{Tt}^2 \\ & - 0.5085\text{Vc}^2 + 0.4096\text{f}^2 + 0.2773\text{a}^2 + 0.4118(\text{Env}*\text{Tt}) + \\ & 0.4262(\text{Env}*\text{f}) + 0.0760(\text{Env}*\text{a}) + 0.0525(\text{Tt}*\text{f}) - \\ & 0.0052(\text{Tt}*\text{a}) + 0.1317(\text{Vc}*\text{f}) + 0.2659(\text{f}*\text{a}) \end{aligned} \quad (3)$$

Fig. 4 validates the model developed for surface roughness (Ra). Correlation factor between experimental and calculated value was found to be 0.9676 which indicates model holds good for predicting the Ra value.

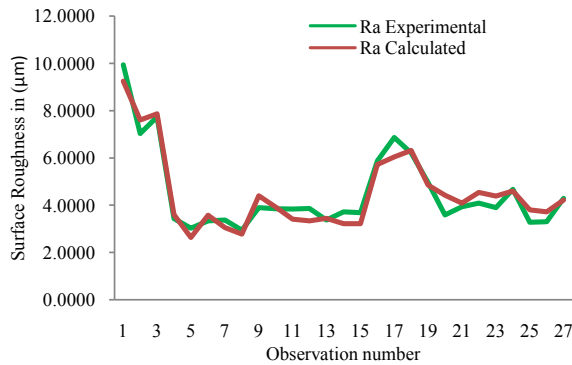


Fig. 4 : Validation of Model for Surface Roughness

4.2.2 RSM model for material removal rate (MRR)

Table 8 shows ANOVA results for MRR model. The p-value for almost all input parameters except cutting environment is less than 0.05 which indicates that the terms Tool Type, and Process parameters speed, feed and depth of cut have strong influence on the MRR. The model is also significant as per the results shown. The values of $R^2 = 97.22\%$ and $R^2(\text{adj}) = 92\%$ demonstrate close significance of the model. Eq. 4 represents the model obtained for MRR using RSM.

Table 8 : Analysis of Variance results for Material Removal Rate (MRR) (Significant terms Only)

Source	DF	Seq SS	Adj SS	Adj MS	F	p
Regression	17	1463.0	1463.0	86.061	18.52	0.000
Linear	5	949.74	439.28	87.856	18.90	0.000
Tt	1	103.84	236.54	236.54	50.90	0.000
Vc	1	343.26	232.33	232.33	49.99	0.000
f	1	241.34	36.65	36.645	7.89	0.020
a	1	198.85	71.74	71.737	15.44	0.003
Square	5	309.86	386.88	77.377	16.65	0.000
Env * Env	1	52.35	52.35	52.347	11.26	0.008
Tt * Tt	1	75.27	75.27	75.269	16.20	0.003
Vc * Vc	1	141.60	218.63	218.62	47.04	0.000
a*a	1	38.56	38.56	38.560	8.30	0.018
Interaction	7	203.44	203.44	29.063	6.25	0.007
Env*Tt	1	54.81	93.99	93.991	20.22	0.001
Env*f	1	2.42	30.92	30.916	6.65	0.030
Env*a	1	11.87	40.97	40.969	8.82	0.016
Tt*a	1	1.76	47.44	47.442	10.21	0.011
Vc*f	1	70.79	70.79	70.795	15.23	0.004
f*a	1	39.78	39.78	39.784	8.56	0.017
Residual	9	41.83	41.83	4.647		
Error						
Total	26	1504.8				
Std. Deviation		2.15579		R-Sq =		97.22%
Press		359.963		R-Sq(adj) =		91.97%

$$\begin{aligned} \text{MRR} = & 18.4114 + 3.1327\text{Env} + 34.5809\text{Tt} - 45.8682\text{Vc} - \\ & 16.0796\text{f} + 20.8425\text{a} + 2.9537\text{Env}^2 - 3.5419\text{Tt}^2 + \\ & 10.4553\text{Vc}^2 + 0.5890\text{f}^2 - 2.5351\text{a}^2 - 5.5973(\text{Env}*\text{Tt}) \\ & + 2.0722(\text{Env}*\text{f}) - 3.0173(\text{Env}*\text{a}) - 0.1615(\text{Tt}*\text{f}) - \\ & 3.2469(\text{Tt}*\text{a}) + 4.2070(\text{Vc}*\text{f}) + 2.5750(\text{f}*\text{a}) \end{aligned} \quad (4)$$

Fig. 5 justifies the trueness of the model with correlation coefficient of 0.9860. The experimental and calculated values are closely matching which proves soundness of the model.

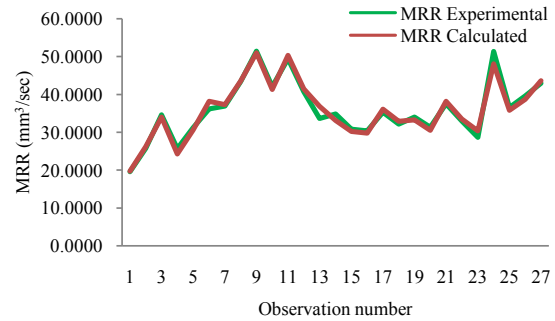


Fig. 5 : Validation of Model for MRR

4.2.3 RSM model for power required during machining (P)

Table 9 indicates the ANOVA results for power required during machining. Small p-value for the regression suggest model is significant. Power required for machining by large depends on machining environment, tool type and cutting speed while feed and depth of cut has no significance. Eq. 5 represents the RSM model for power required during machining. The values of $R^2 = 98.05\%$ and $R^2(\text{adj}) = 94.36\%$ reveal significance of the model.

Table 9 : Analysis of Variance results for Power Required (P) (Significant terms Only)

Source	DF	Seq SS	Adj SS	Adj MS	F	p
Regression	17	0.008437	0.008437	0.000496	26.60	0.000
Linear	5	0.002049	0.005179	0.001036	55.52	0.000
Env	1	0.001625	0.003381	0.003381	181.24	0.000
Tt	1	0.000050	0.000098	0.000098	5.27	0.047
Vc	1	0.000085	0.000122	0.000122	6.56	0.031
a	1	0.000137	0.000066	0.000066	3.54	0.093
Square	5	0.006110	0.006170	0.001234	66.15	0.000
Env * Env	1	0.005971	0.005971	0.005971	320.09	0.000
Vc * Vc	1	0.000036	0.000096	0.000096	5.16	0.049
Residual	9	0.000168	0.000168	0.000019		
Error						
Total	26	0.008605				
Std. Deviation		2.15579		R-Sq =		97.22%
Press		359.963		R-Sq(adj) =		91.97%

$$\begin{aligned} P = & - 0.071746 + 0.130744\text{Env} - 0.022287\text{Tt} + 0.033281\text{Vc} \\ & + 0.010216\text{f} - 0.020002\text{a} - 0.31457\text{Env}^2 + 0.000806\text{Tt}^2 - \\ & 0.006936\text{Vc}^2 - 0.000858\text{f}^2 + 0.003954\text{a}^2 + 0.004491(\text{Env}*\text{Tt}) - \\ & 0.002110(\text{Env}*\text{f}) + 0.000092(\text{Env}*\text{a}) + 0.002302(\text{Tt}*\text{f}) + \\ & 0.001798(\text{Tt}*\text{a}) - 0.003856(\text{Vc}*\text{f}) - 0.001179(\text{f}*\text{a}) \end{aligned} \quad (5)$$

Fig.6 reveals the close relationship between experimental and calculated values with correlation factor of 0.9901.

4.2.4 Response optimization for sustainability

The objective was to optimize the influencing parameters to improve sustainability of a machining process. The goal was set to keep power consumption to minimum, surface roughness to minimum and to maximize material removal

rate. Relative importance was provided accordingly as shown in table 9.

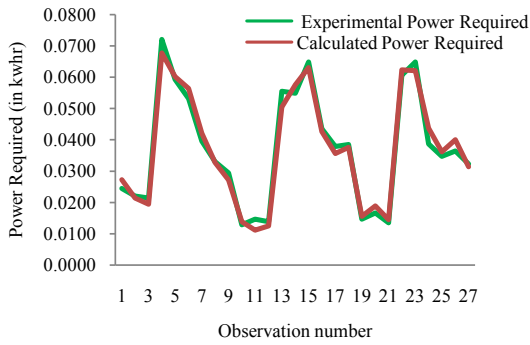


Fig. 6 : Validation of Model for Power Required for Machining (P)

Table 9 : Parameter conditions for Optimization

	Goal	Lower	Target	Upper	Weight	Importance
Ra	Min	2.9500	2.9500	6.4500	1	2
MRR	Max	35.5000	51.4500	51.450	1	3
P	Min	0.0129	0.0129	0.0424	1	1

Table 10 : Global Solution

Parameter	Opt. Value
Environment	1
Tool type	2.57576
Cutting Speed	3
Feed	3
Depth of cut	1.67016

Table 11 : Predicted Responses

Parameter	Output	Desirability
Ra	2.7623	1.000000
MRR	53.6737	1.000000
P	0.0040	1.000000

Table 10 shows the global solution obtained by performing the RSM optimization using Minitab 16. Dry environment with TiAlN coated tool, cutting speed = 50.55 m/min, feed=0.2107 mm/rev and depth of cut =1 are the optimized values for given conditions. The values in fraction are rounded off to next higher level. Table 11 shows the predicted values of the responses for the optimized solution.

5. Conclusion

Conventional machining was selected in this study. Sustainability issues related to economic and environmental aspect in the form of surface roughness, material removal rate and power consumption were studied. Experiments were conducted with varying conditions for speed feed, depth of cut, machining environment and cutting tool type. Taguchi analysis was performed to understand the ranking of factors affecting the response. The process was modelled using response surface methodology (RSM). ANOVA results were obtained to understand the significance of the model developed.

Study has revealed that surface roughness by large is influenced by cutting environment and the kind of tool. It was also found that material removal rate is influenced by tool type, cutting velocity, feed and depth of cut while power required for machining depends on cutting environment, tool type cutting velocity and depth of cut. The experimental and the results obtained from model are closely related. The results found are in line with the previous studies by various researchers.

The results were optimized from sustainability point of view providing importance to power consumption and to

keep it to minimum. The outcome of the model facilitate for setting machining parameters to accomplish the objective. Future work will cover more critical analysis of input parameters from overall sustainability point of view and to assess sustainability of conventional turning process.

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