Tanzania Journal of Engineering and Technology 2025, **44**(2):287-294
OPEN ACCESS articles distributed under Creative Commons Attribution Licence [CC BY-ND]
Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v44i2.1306

Special Issue – 8th International Conference on Mechanical and Industrial Engineering, October 24 – 25, 2024 at The Nelson Mandela African Institute of Science and Technology, Arusha - Tanzania

Effects of Cutting Conditions on Tool Temperature and Material Removal Rate in Turning Operations

Simon I. Marandu† and Brian C. Ngowi

Department of Mechanical and Industrial Engineering, College of Engineering and Technology, University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania

†Corresponding Author: marandus15@gmail.com; ORCID: 0000-0001-6248-3819

ABSTRACT

Cutting conditions in manufacturing processes have effects on tool temperature and material removal rate. The objective of this study was to investigate the effects of cutting conditions namely spindle speed, feed rate, depth of cut and tool nose radius on tool temperature and material removal rate in turning operations. A total of 81 experiments were conducted to measure tool temperature and material removal rate in order to determine the effects of cutting conditions on tool temperature and material removal rate using ANOVA and regression analysis. The results show that tool nose radius, depth of cut, and spindle speed are significant to tool temperature, whereas feed rate is insignificant to tool temperature. Tool nose radius has the highest contribution to tool temperature with 44.43%, followed by spindle speed with 6.96%, depth of cut with 6.52%, and then feed rate with 0.08%, all with an error of 42.01%. In addition, spindle speed, feed rate, and depth of cut are significant to material removal rate while the tool nose radius is insignificant to material removal rate. The most important factor is feed rate, which contributes to 39.8%, followed by the depth of cut with 21%, spindle speed with 4.86%, and tool nose radius with 0.71% and an overall 33.64% contribution to the error. The findings conclude that tool nose radius may be closely controlled for generation of lower tool temperature while feed rate and depth of cut need to be thoroughly monitored to take advantage of higher productivity.

ARTICLE INFO
Submitted: **Apr. 1, 2024**
Presented: **Oct. 25, 2024**
Revised: **Nov. 22, 2024**
Accepted: **Feb, 30, 2025**
Published: **June, 2025**

Keywords: Turning operation, cutting conditions, design of experiment, tool temperature, material removal rate (MRR)

INTRODUCTION

Turning is one of the most common manufacturing processes used to convert a cylindrical raw stock into a finish product. In the metal cutting processes, majority of power is converted into heat, thus resulting in extremely high cutting temperatures within the cutting zone thus making it one of the essential aspects of the metal cutting process (Ososomi and Ekhayeme, 2022). During cutting of a workpiece, heat is generated at the cutting point from three sources which are primary shear zone, secondary deformation zone at the chip–tool interface, and tertiary zone which is work-tool interface (Akhil *et al*., 2016). The temperature rise in the cutting zone may create thermal stresses in the machined material and lead to the distortions of its surface thus control of the cutting temperature is required in order to achieve the desired tool performance and product quality. Muller-Hummed *et al.* (1996) stated that the heat conductivity and specific heat capacity of the tool and work piece, as well as the amount of heat lost by radiation and convection affect the temperature distribution. The temperature rises to its peak in the area where the chip and tool come into contact. The work piece, chip, tool, and ultimately the environment is all affected by the heat created in the contact areas involving the tool-chip and tool-workpiece interfaces.

Despite the fact that the heat produced at the shearing plane facilitates cutting, it can also seep into the cutting edge, shortening the tool life. The temperature of the chip-tool contact must thus be monitored during metal cutting. At the tool-chip contact, temperature and normal stress are essential aspects that might cause wear and material degradation of the work piece (Madalina *et al.*, 2012). Nedic´ and Eric´ (2014) conducted experimental tests on cutting temperature measurement and material machinability and revealed that cutting forces are transformed into heat. The work piece, chip, tool, and ultimately the environment is affected by the heat created in such the interface areas. The environment makes the cutting wedges softer, which causes the tool to become blunted, distorted, lose its cutting capabilities, and degrading toughness of the cutting components. The heat produced during the cutting operation also affects other machining process output characteristics, such as the productivity of the process, the quality of the treated surface, and the machining accuracy, in addition to its effect on tool life. The cutting tool geometry such as the tool nose radius is also of prime importance in machining performance because it directly affects chip control, productivity of machining, tool life, the direction and magnitude of the cutting force, and quality of machining. In addition to cutting temperature, the impact of cutting tool geometry on turning dynamics has long been a problem. Chip development, heat production, tool wear, and surface quality during turning are significantly influenced by tool geometry. Therefore, given the importance of cutting conditions in metal cutting processes, it is essential to investigate their effects on tool temperature and material removal rate.

Although tool temperature and material removal rate have opposing performance characteristics, they form valued machining performance in manufacturing shop floor. On the other hand, Jha (2014) argued that higher MRR was desired by the industry for fast production in short time, which could be improved by increasing the process parameters namely cutting speed, feed and depth of cut. Nevertheless, high cutting speed need more power and at the same time temperature between tool and work-piece increase, which is detrimental in both the product and tool. So, understanding the effects of process parameters in turning operations is vital in order to determine the efficiency and overall economy of the product in achieving higher MRR. Thus, the objective of this study was to investigate the effects of cutting conditions namely spindle speed, feed rate, depth of cut and tool nose radius on both tool temperature and material removal rate in the turning operations.

METHODS AND MATERIALS

Dry machining experiments were conducted in the Production Engineering laboratory at the University of Dar es Salaam. The workpiece material was AISI 1020 Mild steel rod with a chemical composition of 0.173%C, 0.029%S, 0.516% Mn, 0.158%Si and 0.075% P. The workpiece was 40 mm diameter, 300 mm long with actual cutting length of 270 mm. The cutting tool was carbide inserts, type H, grade H 10 for high temperatures alloy steels. A full factorial design of experiment was used to set a combination of experiments to measure the cutting temperature and material removal rate. As such, 81 experiments were designed based on 4 cutting conditions viz. spindle speed, depth of cut, feed rate and tool nose radius each with 3 levels were selected within the operating range of the cutting conditions of the lathe machine as shown in Table 1.

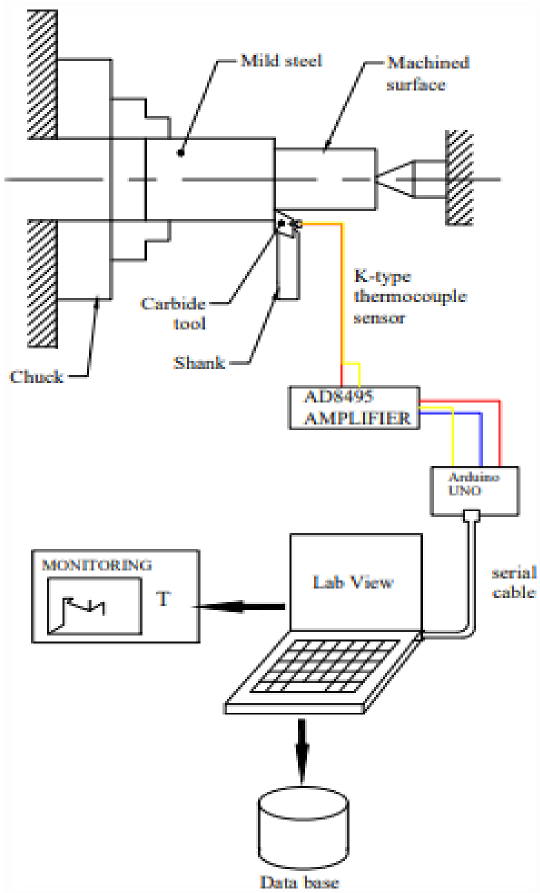
Data were collected through a series of machining experiments performed on an HEIDEIN REICH and HARBEK VDF 21 RO Lathe machine. The experimental setup is presented in Figure 1, where analog K-type thermocouple sensor was inserted into the rake face of the carbide insert and tool holder to acquire the average tool temperature, and process it using a Lab VIEW software. The Arduino UNO R3 board acted as a communication bridge and computer (Atmel358P). The thermocouple sensor was fed through an amplifier to connecter to the analog input pins 6,7, and 8 of the Arduino UNO. A +5V Power supply was required for the amplifier, and it was incorporated inside the Arduino board. The signal was transmitted to the coded LabVIEW program through a serial connection. A Mettler Toledo digital weighing scale with a maximum measuring capacity of 4100 g and a minimum measuring capacity of 0.5 g and an accuracy of ± 0.01 g was used to measure the weight of the workpiece before and after machining in order to calculate the material removal rate (MRR) given by

$$MRR = \frac{w_1 - w_2}{\rho \times t} \qquad (1)$$

where w_1 = original work piece weight (g), w_2 = finished work piece weight (g), t = cutting time (min), and ρ = density (g/cm^3).

Table 1: Cutting conditions and their levels

S/N	Cutting conditions	Level 1	Level 2	Level 3
1	Spindle speed (rpm)	355	425	500
2	Depth of cut (mm)	1.0	1.5	2.0
3	Feed rate (mm/rev)	0.2	0.4	0.8
4	Nose radius (mm)	0.4	0.8	1.2



Note: T indicates Temperature

Figure 1: Machining experimental setup.

Analysis of variance (ANOVA) in Minitab version 21 software was used to determine the most significant cutting condition that affects tool temperature and material removal rate. This was followed by formulating regression models for cutting temperature and material removal rate using a multiple linear regression equation presented in the in equation 2. Linear regression equations are simple and faster in solving; they are commonly used in experimental studies.

$$Y = b_0 + b_1 n + b_2 f + b_3 d + b_4 r \qquad (2)$$

where Y is dependent variable; n, f, d, and r are independent variables; b_0 = intercept term; and b_1, b_2, and b_3 = slopes coefficient.

RESULTS AND DISCUSSIONS

The objective of this study was to ascertain how cutting conditions such as spindle speed, feed rate, depth of cut, and tool nose radius affect machining performance on the tool temperature and material removal rate in turning operations. The combined results of the machining experiments are presented in Table 2 in which the tool temperature and material removal rate were measured.

Table 2: Machining experimental results

S/N	Spindle speed [rpm]	Feed rate [mm/rev]	Depth of cut [mm]	Nose radius [mm]	Tool temperature [ºC]	MRR [mm^3/min]
1	355	0.2	1	0.4	83.75	2041.04
2	355	0.2	1.5	0.4	94.25	3109.76
3	355	0.2	2	0.4	112.5	4486.89
4	355	0.4	1	0.4	69.5	3578.83
5	355	0.4	1.5	0.4	78.5	5691.81
6	355	0.4	2	0.4	86.25	7349.46
7	355	0.8	1	0.4	106	5506.82
8	355	0.8	1.5	0.4	132.25	11943.3
9	355	0.8	2	0.4	77.25	13576.1
10	425	0.2	1	0.4	60.5	2041.08
11	425	0.2	1.5	0.4	84	5424.54
12	425	0.2	2	0.4	81.25	3876.93
13	425	0.4	1	0.4	71	4779.55
14	425	0.4	1.5	0.4	70.25	6385.55
15	425	0.4	2	0.4	92.5	10984.9
16	425	0.8	1	0.4	82.25	6110.95
17	425	0.8	1.5	0.4	102.5	12004.8
18	425	0.8	2	0.4	90.75	12465.7
19	500	0.2	1	0.4	64.5	2473.54
20	500	0.2	1.5	0.4	75.75	4083.71
21	500	0.2	2	0.4	93.75	7549.99
22	500	0.4	1	0.4	63	4063.3
23	500	0.4	1.5	0.4	77.5	10376.6
24	500	0.4	2	0.4	101.5	11057.9
25	500	0.8	1	0.4	117.5	8730.72
26	500	0.8	1.5	0.4	77.25	18525.2
27	500	0.8	2	0.4	72.75	17700
28	355	0.2	1	0.8	90.5	1898.35
29	355	0.2	1.5	0.8	100.25	3081.13
30	355	0.2	2	0.8	112.75	4232.95
31	355	0.4	1	0.8	109.5	4043.44
32	355	0.4	1.5	0.8	101	5136.75
33	355	0.4	2	0.8	109.25	7545.54
34	355	0.8	1	0.8	76.75	5090.98
35	355	0.8	1.5	0.8	104.5	9049.53
36	355	0.8	2	0.8	103	9878.56
37	425	0.2	1	0.8	78	2811.31
38	425	0.2	1.5	0.8	115	16094.5
39	425	0.2	2	0.8	132.5	6055.07
40	425	0.4	1	0.8	104.75	5914.17
41	425	0.4	1.5	0.8	93.75	7756.06
42	425	0.4	2	0.8	116.25	9485.56
43	425	0.8	1	0.8	99.5	9493.36
44	425	0.8	1.5	0.8	104.25	13358.2
45	425	0.8	2	0.8	87.05	17520.7
46	500	0.2	1	0.8	65	3898.12
47	500	0.2	1.5	0.8	86	4750.04
48	500	0.2	2	0.8	107.25	7244.6

49	500	0.4	1	0.8	101.75	3275.89
50	500	0.4	1.5	0.8	95.75	3989.01
51	500	0.4	2	0.8	114	11240.2
52	500	0.8	1	0.8	106.25	8450.08
53	500	0.8	1.5	0.8	95.5	14642.4
54	500	0.8	2	0.8	94.5	11077.6
55	355	0.2	1	1.2	152.5	9434.78
56	355	0.2	1.5	1.2	198	3852.45
57	355	0.2	2	1.2	178.5	4418.22
58	355	0.4	1	1.2	115.5	3102.35
59	355	0.4	1.5	1.2	127.5	6082.67
60	355	0.4	2	1.2	124	16021
61	355	0.8	1	1.2	102.25	5708.4
62	355	0.8	1.5	1.2	152.75	8094.58
63	355	0.8	2	1.2	164.25	9252.45
64	425	0.2	1	1.2	101	2885.4
65	425	0.2	1.5	1.2	142.5	3558.08
66	425	0.2	2	1.2	148.75	4381.27
67	425	0.4	1	1.2	119.75	4265.18
68	425	0.4	1.5	1.2	135.25	8469.46
69	425	0.4	2	1.2	140	10694.7
70	425	0.8	1	1.2	129.5	10369.1
71	425	0.8	1.5	1.2	128.75	15499.1
72	425	0.8	2	1.2	112.5	18427.8
73	500	0.2	1	1.2	98.75	3834.08
74	500	0.2	1.5	1.2	107	4376.07
75	500	0.2	2	1.2	112.5	5805.54
76	500	0.4	1	1.2	90	6593.12
77	500	0.4	1.5	1.2	103	9231.59
78	500	0.4	2	1.2	113.75	13972.3
79	500	0.8	1	1.2	109.75	8585.63
80	500	0.8	1.5	1.2	131.75	14531.5
81	500	0.8	2	1.2	130.75	19671.1

The effects of spindle speed, feed rate, depth of cut, and tool nose radius on the cutting temperature were determined using a main effect plot of the Minitab software as shown in Figure 2. The figure shows that increasing the spindle speed will decrease the tool temperature. This might be caused by less time of generating the heat on the surface due to higher spindle speed. The tool nose radius and depth of cut are directly proportional to cutting temperature indicating that the bigger the nose radius and depth of cut the higher the chip formation resulting in increased heat generation. Feed rate fluctuates with tool temperature, demonstrating that feed rate may have no considerable effect on the tool temperature. The tool nose radius has the highest contribution to the tool temperature with 44.43%, followed by the spindle speed with 6.96%, the depth of cut with 6.52%, and the feed rate with 0.08%, all with an error of 42.01%. However, Ososomi and Ekhayeme (2022), Farooq and Jahanzaib (2014) revealed that the cutting temperature rises at higher depth of cut and feed rate showing that also the feed rate positively contributes to the cutting temperature at higher rates.

Additionally, Figure 3 shows how machining performance of material removal rate is affected by the spindle speed, feed rate, depth of cut, and tool nose radius. As noted in the figure, all cutting conditions are directly related to the rate of material removal informing that increasing the spindle speed, feed rate, depth of cut, and tool nose radius results in increased productivity. However, the p-value of tool nose radius was more than 0.05; thus, making it insignificant to the material removal rate. The p-values of the spindle speed, feed rate, and depth of cut were less than 0.05; making them significant to the material removal rate. The most important factor is the feed rate, which contributes 39.8%, followed by depth of cut with 21%, spindle speed with 4.86%, and tool nose radius with 0.71%, all with a 33.64% contribution to the error. This fact is similar to the findings by Dave *et al*., (2012), Mukherjee *et al*. (2014) which showed that depth of cut, feed rate, tool nose radius and spindle speed have positive influence on the material removal rate.

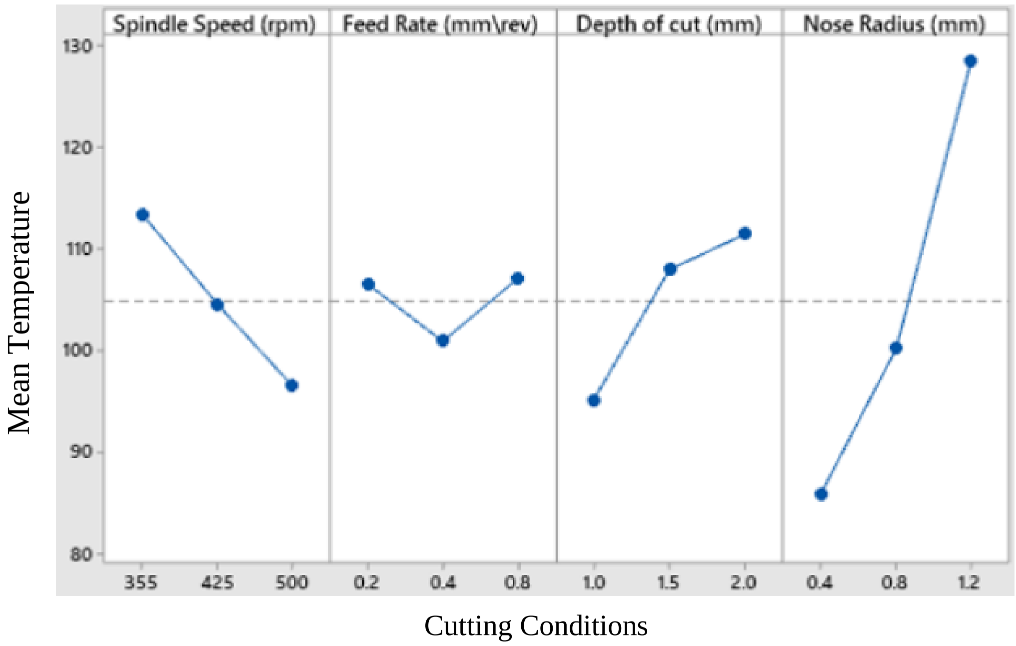


Figure 2: Effects of cutting conditions on tool temperature (°C).

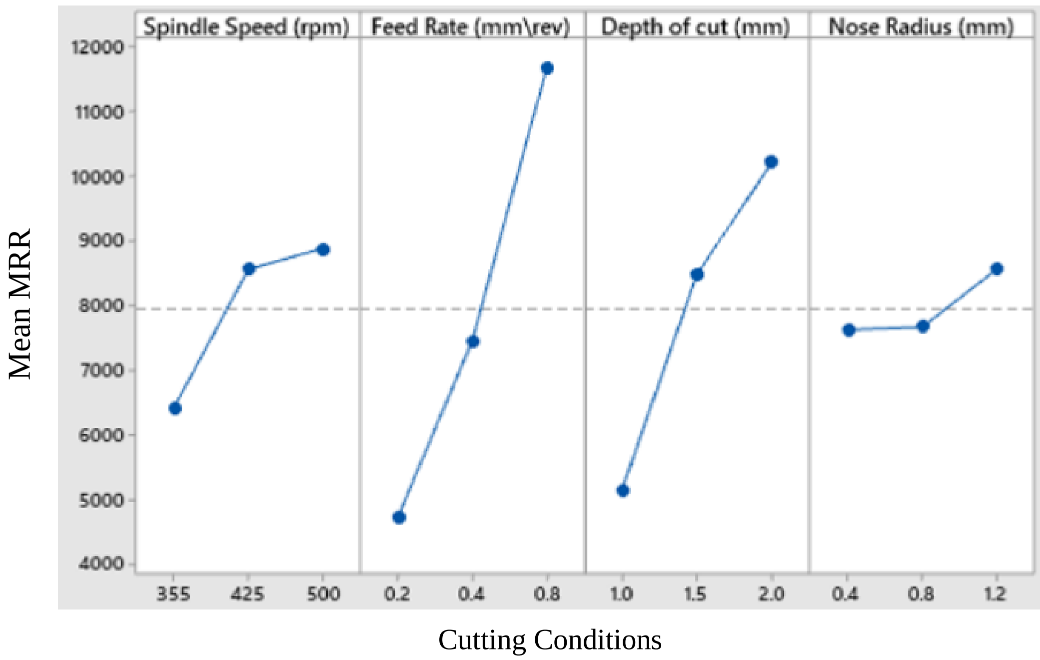


Figure 3: Effects of cutting conditions on material removal rate.

The regression analysis reported *R*-squared score of 58% for the tool temperature with an *R* value of 76% indicating that the tool temperature model is capable of reproducing the results. Similarly, the regression analysis reported the *R*-squared score of 66.36% for the material removal rate with an *R* value of 81% which confirms the appropriateness of the model. The results match well with those established by Jha (2014) and Mukherjee *et al*., (2014). The regression equations for tool temperature and material removal rate are respectively presented in the equations 3 and 4 as:

$$Temperature\ (°C) = 86.0 - 0.1164n + 16.34d + 53.32r \quad (3)$$

$$Material\ removal\ rate\ \left(\frac{mm^3}{\min}\right) = -13114 + 16.84n + 11434f + 5074d \quad (4)$$

where *n* is spindle speed (rpm), *f* is feed rate (rev/mm), *d* is depth of cut (mm) and *r* is tool nose radius (mm). As noted in both regression equations, the feed rate is dropped in the tool temperature model because it is insignificant to the tool temperature generation while the tool nose radius is omitted in the material removal rate model because it is insignificant to material removal rate.

CONCLUSION

The main objective of the study was to determine the relationship between cutting conditions and machining performance. The study was limited to dry machining because the carbide tool and online measurement of temperature did not favour wet machining, thus providing an area for further study. The cutting conditions in question were spindle speed, feed rate, depth of cut and tool nose radius while the machining performance were the tool temperature and material removal rate. The results show that tool nose radius, depth of cut, and spindle speed are significant to the generation of tool temperature, whereas feed rate is insignificant. The tool nose radius has the highest contribution to the tool temperature followed by spindle speed, depth of cut and the feed rate. Furthermore, spindle speed, feed rate, and depth of cut are significant to the material removal rate while the tool nose radius is not important. The most important factor is the feed rate, followed by the depth of cut, the spindle speed, and lastly the tool nose radius. The results provide an insight that the tool nose radius may be closely controlled for lower tool temperature of while the feed rate and depth of cut need to be thoroughly monitored for higher productivity. However, there is a need of more investigation to determine the optimum cutting conditions that will meet both performance objectives of lower tool temperature and higher productivity.

REFERENCES

Akhil, C.S., Anantha Vishnu, H. M., Akhil, C. K., Afeez, M. P., and Rajan, R. (2016.). Measurement of Cutting Temperature during Machining. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, *13*(2): 108–122.

Madalina, C., Dominique, C. and Franck G. (2012). Strain field Measurement in Orthogonal Machining of a Titanium alloy. *Advanced Materials Research*, *498*:237-242.

Dave, H. K., Patel, L. S., and Raval, H. K. (2012). Effect of machining conditions on MRR and surface roughness during CNC turning of different materials using TiN coated cutting tools - A Taguchi approach. *International Journal of Industrial Engineering Computations*. *3*(5):925–930.

Farooq, H. and Jahanzaib, M. (2014). Optimization of Process Parameters for Temperature Distribution in Orthogonal Metal Cutting. *Quaid-E-Awam University Research Journal of Engineering, Science and Technology*, *13*(2): 11-19.

Jha, S. K. (2014), Optimization of Process Parameters for Optimal MRR during Turning of Steel bar Using Taguchi Method and ANOVA, *International Journal Mechanical Engineering and Robotics Research*, *3*(3):231-232.

Mukherjee, S., Kamal, A., and Kumar, K. (2014). Optimization of Material Removal Rate During Turning of SAE 1020 Material in CNC Lathe using Taguchi Technique. *Procedia Engineering*, *97*:29–35.

Muller-Hummed, P., and Lahr's, M. (1996). A New Instrument to Optimize Cutting Process in Situ Temperature

Measurement on Diamond Coated Tools. *Innovations in Material Research*, *1*:1-9.

Nedic´, B. P., and Eric´, M. D. (2014). Cutting temperature measurement and material machinability. *Thermal Science*, *18:* 259–268.

Ososomi, A. S., and Ekhayeme, M. O. (2022). The Effect of Parameters and Optimization of Surface Roughness and Cutting Temperature in Turning of AISI 1020 Carbon Steel using Taguchi Technique and ANOVA. *Direct Research Journal of Engineering and Information Technology 9*(4):192-200.