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OPTIMIZATION OF MACHINING PARAMETERS IN TURNING PROCESS OF MDN431 USING TI-MULTILAYER COATED TOOL

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Abstract: WC-Co Cutting tool inserts are coated with tailored composition of Ti/TiCN/TiN/TiCN/TiN using cathodic arc evaporation technique. MDN431 is one of highly alloyed steel with tailored mechanical properties. MDN431 material is machined with Ti/TiCN/TiN/TiCN/ TiN coated and uncoated Co-based WC tool inserts. Machining parameters; cutting speed (398-625rpm), feed rate (0.093-0.175mm/rev) and depth of cut (0.1-0.5mm) and experiments are conducted according to response surface methodology center composite rotatable design. Surface roughness and cutting forces are measured for each iteration and the same analyzed for significance. Result reveals that for optimum surface roughness is obtained at the condition of high speed, low feed and low depth of cut. For optimum cutting force high speed, low feed and low depth of cut is preferred. Coated tools performed better in the study with increased tool life, reduced cutting force & surface roughness. At the optimum machined conditions machined surface are analyzed using optical profilometer. Central composite rotatable design developed mathematical models for cutting force and surface roughness for the prediction of results. The predicted results are minimum error and developed model is adequate for further usage.

Key words: Ti-Thin film coating, Cathodic arc evaporation, RSM optimization, Thin solid films; Optical profilometer.

1. INTRODUCTION

Turning in manufacturing is reported as versatile machining process in the industrial sector. Optimization of machining processes gained lot of importance in the manufacturing process due to significant increase in production and to reduce the capital investments. Improvisation of the machining process is done by various methods which include proper selection of machining combination, cutting tool and machine tool. Improvisation is assessed by cutting forces, surface roughness characteristics, power and tool life. Development of the thin film coating on the cutting tool is a breakthrough in manufacturing sector (Chinchanikar and Choudhury, 2014; Dumpala et al., 2013; Qin et al. , 2009; Wang et al., 2014). Hard thin films coating namely TiC, TiN, Al_2O_3, TiCN and so on are developed on the cutting tools resulted in improvement of tool life, lower coefficient of friction and the tool wear. Machinability study builds interrelation between the cutting parameters and output response which involves number of experiments to be conducted. Statistical techniques, RSM, Taguchi, factorial design proven its credential on selection and optimization of experiments (Gaitonde et al., 2012; Hiremath et al., 2016; Kadi and Dundur, 2015; Kıvak, 2014). Cr and Ni alloy steels are widely used in manufacturing of turbines and aerospace components. With the customized alloying mechanical properties, strength and hardness are improved which resulted in hard-to-machine steels shown in numerous publications which include inconel, incoloy and other super alloys (Badiger et al., 2015; Garcí et al., 2013; Sivaiah and Chakradhar, 2017).

Angadi et al. (2015) in their studies on drilling characteristics of cenosphere reinforced epoxy composites explained that the effect of feed rate and speed on thrust force and surface roughness. i.e surface roughness and cutting force decrease with the increase in speed and increase with the increase in feed rate. Sharman et al. (2015), in their work explained that the tool life is depended on cutting speed and feed rate, with increase in speed and feed rate tool life has reduced. Sahoo and Sahoo (2012) proposed that multilayer coatings on carbide tools an alternative for tool replacement during its tool wear and suggested that TiN coated inserts performed better in machinability characteristics due to lubricious properties of TiN. It reduces the friction, preventing interface temperature which delays the wear growth. Davim and Figueira (2007) elaborated using statistical analysis optimization and designs of the experiments are done with ease, and contributions of each input variable on the output response are calculated using statistical approach. Bouacha et al. (2010), in his work machinability of AISI 52100 bearing used RSM approach to optimize the cutting force and surface roughness. Depth of cut is the significant influencing factor on cutting force followed by speed and feed rate. Feed rate is the significant influencing factor on surface roughness, speed and depth of cut has negligible effect, he also suggested that RSM approach for machinability studies. Research on machinability characteristics on steel alloys using the coated tools are less in number and statistical techniques are most reliable for the studies involving more number of experiments (Sahoo and Sahoo, 2013; Suresh et al., 2012).

In the current research work, Ti-multilayer coatings are developed on WC tool insert and performance of Ti multilayer coated tool is studied based on effect of machining parameters on cutting forces (F_x, F_y and F_z) and surface roughness (R_a) during the turning of MDN431 steel. Quadratic models are developed using full factorial design and response surface methodology central composite rotatable design. The experimented results and predicted results are compared with each other. Coefficient of determination (R^2) is determined for adequacy.

2. EXPERIMENTAL WORK

Turning work is carried out on MDN431 alloyed steel with the chemical composition shown in Table 1 dimensions of machine sample are 250 mm in length and 30 mm in diameter. Based on operatability of cutting tool and machine tool, the pilot runs are carried out to select the machining parameters. Based on pilot runs the selected machining parameters are represented in Table 2.

Table 1. Chemical composition of MDN431

Material	C	Mn	Si	Cr	Ni	Fe
	%					
MDN 431	0.15	0.7	0.7	17	2.5	Balance

RSM central composite rotatable design array, experimental and predicted results are tabulated in Table 2. Experiments for each combination are repeated to minimize the errors to ensure the accurate readings. Self-centered panther lathe machine tool was used for machining work. Kennametal Germany-make SNMG120408 WC tool insert was attached to the DSSNR2020K12 tool holder. Ti-multilayer coatings were developed using PVD cathodic arc evaporation technique with the composition of Ti/TiN/TiCN/TiN/TiCN. Cutting forces are measured using Kistler 9257B piezoelectric Dynamometer mounted on the tool post with the help of Kistler Dynoware software 2825D-02 data acquisition was done. Surface roughness was measured using the using Mitutoyo SJ301 roughness tester.

Table 2. Experimental conditions

Levels	1	2	3	4	5
Speed, V_c (rpm)	256	398	572	625	796
Feed, f (mm/rev)	0.062	0.093	0.125	0.175	0.2
Depth of cut, a_p (mm)	0.1	0.2	0.3	0.4	0.5

3. RESULTS AND DISCUSSION

3.1 Machinability studies

In the current research work machinability characteristics for MDN431 is studied using Ti-multilayer coated tool. Machinability study is carried out based on response surface methodology central composite rotatable design. 3 factor-5-levels RSM CCR design for machinability with experimental results and predicted results are shown in Table 3.

3.2 Regression models developed form RSM CCR design

Results of RSM analysis for are represented in Figure 1 (a), (b) and (c) represents the main effects plots for cutting forces F_x, F_y and F_z. Figure 1 (d) represents the main effect plots for surface roughness (R_a). Optimization technique adopted for the present work is minimization of the cutting force and surface roughness. Optimum machining condition is obtained with the combination of 0.2mm depth of cut, 625rpm speed and 0.093mm/rev feed rate for least cutting force and surface roughness. Second order regression models are developed using the full factorial design; represented in equations 1-4. Equation 1, 2 and 3 are used to determine the predicted results for F_x, F_y and F_z. Equation 4 is used to determine the predicted results for surface roughness (R_a).

Regression models

$$F_x=((-18.1914) + (805.053\times a_p) + (-0.392776\times V_c) + (1078.43\times f) + (-0.502093\times a_p\times V_c) + (2742.38\times a_p\times f) + (0.701891\times V_c\times f) + (-1688.78a_p^2) + (0.000138844\times V_c^2) + (-8534.08\times f^2)) \quad (1)$$

$$F_y=((62.2129) + (737.939\times a_p) + (-0.460642\times V_c) + (982.446\times f) + (-0.537335\times a_p\times V_c) + (2829.57\times a_p\times f) + (-0.274256\times V_c\times f) +(1684.89\times a_p^2)+(0.000298989\times V_c^2)+ (-4849.19\times f^2)) \quad (2)$$

$$F_z= ((43.8331) + (883.447\times a_p) + (-0.677433\times V_c) + (1322.37\times f) + (0.568392\times a_p\times V_c) + (4755.79\times a_p\times f) + (0.795369\times V_c\times f) + (-1920.99\times a_p^2) + (0.000348446\times V_c^2) + (-8908\times f^2)) \quad (3)$$

$$R_a= ((4.28176) + (1.609\times a_p) + (-0.00729821\times V_c) + (-31.0385\times f) + (0.000734214\times a_p\times f) + (0.813008\times a_p\times f) + (-0.00823753\times V_c\times f)+(-3.30074\times a_p^2)+(6.95203e^{(-006)}\times V_c^2)+(163.696\times f^2)) \quad (4)$$

Table 3. RSM CCRD experimental design with results

Process parameters			Experimental Results				Predicted Results			
a_p [mm]	V_c [rpm]	f [mm/rev]	F_x [N]	F_y [N]	F_z [N]	R_a [μm]	F_x [N]	F_y [N]	F_z [N]	R_a [μm]
0.1	572	0.125	41.75	109.7	90.94	0.95	14.05	81.85	59.39	0.80
0.2	625	0.093	30.33	83.01	79.59	0.64	86.92	147.08	133.71	0.84
0.2	398	0.175	55.85	157.6	150.8	1.64	60.04	163.22	161.03	1.81
0.2	398	0.093	50.29	109.9	105.7	0.71	78.70	134.01	139.98	0.96
0.2	625	0.175	44.62	133.9	128.2	1.55	46.57	132.12	146.22	1.48
0.3	572	0.125	132.2	195.4	229.1	0.91	124.83	187.74	219.00	0.86
0.3	572	0.125	132.2	195.4	229.1	0.91	124.83	187.74	219.00	0.86
0.3	572	0.125	132.2	195.4	229.1	0.91	124.83	187.74	219.00	0.86
0.3	572	0.125	132.2	195.4	229.1	0.91	124.83	187.74	219.00	0.86
0.3	572	0.125	132.2	195.4	229.1	0.91	124.83	187.74	219.00	0.86
0.3	796	0.125	162.1	229	266.6	0.88	159.49	223.96	262.91	1.01
0.3	572	0.125	132.2	195.4	229.1	0.91	124.83	187.74	219.00	0.86
0.3	572	0.2	71.23	172.4	244	2.20	86.90	191.10	233.05	2.18
0.3	256	0.125	157.7	225.8	279.8	1.72	139.58	210.38	252.37	1.40
0.3	572	0.062	157.3	214.5	192.3	1.45	99.35	153.28	134.31	1.14
0.4	398	0.175	151.9	253.1	299.3	1.73	155.83	252.18	314.00	1.83
0.4	398	0.093	105.7	150.7	187.5	0.66	125.19	172.31	212.85	0.96
0.4	625	0.093	104.2	156.5	175.9	0.76	145.72	199.44	227.30	0.86
0.4	625	0.175	167.8	245.5	313.8	1.55	154.66	235.14	319.90	1.52
0.5	572	0.125	172.4	228	321.4	0.95	164.37	219.53	299.40	0.84

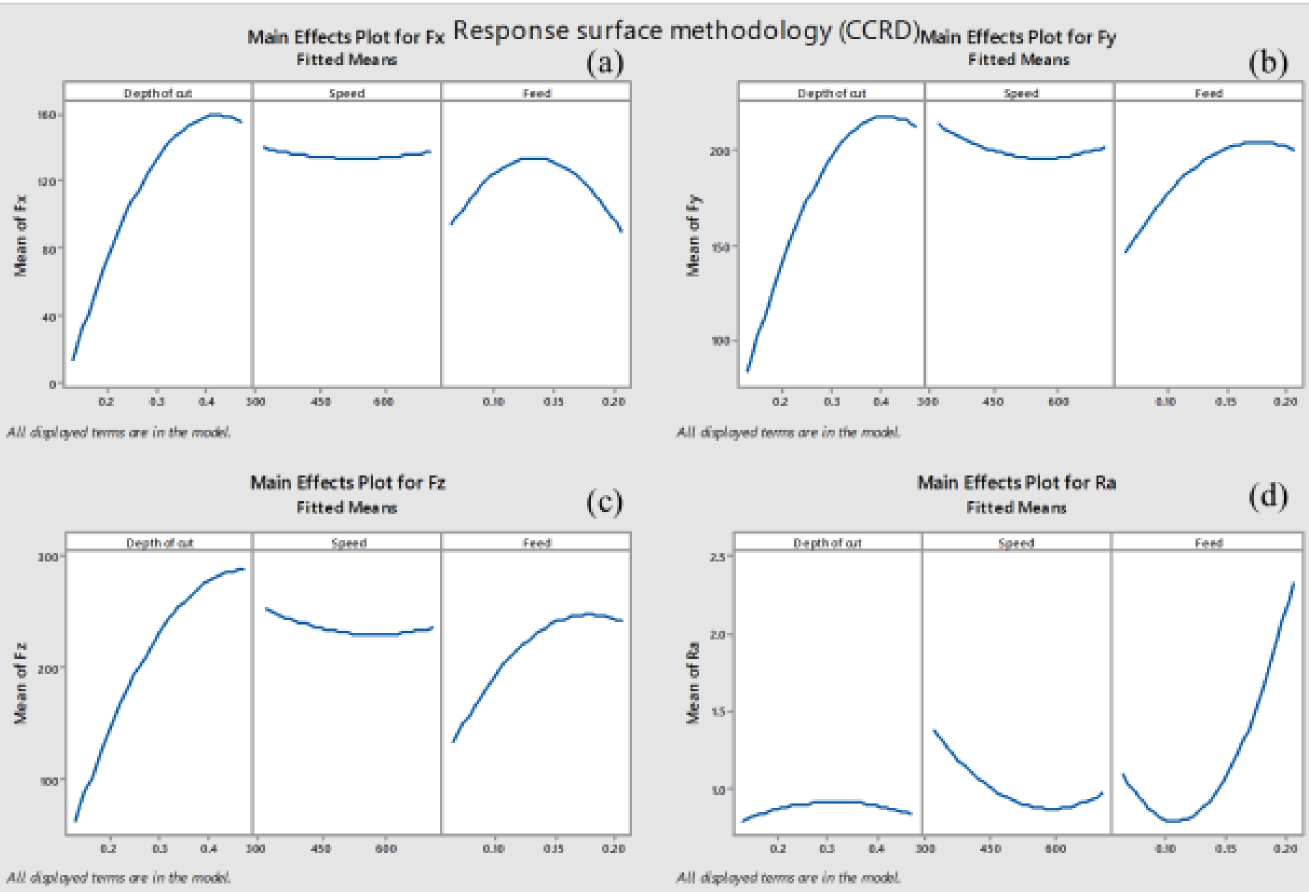

Fig. 1. Main effect plots for RSM analysis

Table 4. Anova result summary for RSM CCRD

Response	Sum of squares		Degrees of freedom		Mean square		F ratio	P*	CoD (R^2)
	Regression	Residual	Regression	Residual	Regression	Residual			
F_x [N]	31780.9	10505.7	9	10	3531.21	1050.57	3.36	0.03	0.7516
F_y [N]	30142.7	12177.4	9	10	3349.19	1217.74	2.75	0.06	0.7123
F_z [N]	85314	11498.7	9	10	9479.33	1149.87	8.24	0.00	0.8812
R_a [μm]	3.23	0.54	9	10	0.36	0.05	6.69	0.00	0.8576

* significant at 95% confidence level

Table 5. Validation results for RSM CCRD model

a_p	V_c	f	Exp F_x	Pred F_x	Exp F_y	Pred F_y	Exp F_z	Pred F_z	Exp R_a	Pred R_a
[mm]	[rpm]	[mm/rev]	[N]	[N]	[N]	[N]	[N]	[N]	[μm]	[μm]
0.15	196	0.046	47.45	50.38	89.12	87.74	106.55	112.18	1.83	1.80
0.25	384	0.078	85.18	88.88	139.20	137.51	152.39	147.76	0.99	1.06
0.35	796	0.175	150.6	156.50	224.54	230.26	319.71	322.46	1.61	1.58

3.3 Analysis of cutting force

Figure 2 (a-c) depict the interaction effects of cutting force for Ti-multilayer coated tool. The effect of feed rate and depth of cut are observed that with increase in feed rate and depth of cut linearly affects the cutting force. For less feed rate and depth of cut, cutting force is reduced and with increase in feed rate and speed steady rise in the cutting force are observed. Speed is not much influencing the cutting forces during machining. With increase in depth of cut slight change in cutting forces are observed. Depth of cut and feed rate are contributing more (affecting the cutting force) in RSM analysis compared to speed (Angadi et al., 2015; Bouacha et al., 2010). Anova Table 3 shows that the regression models developed for cutting forces and surface roughness are significant ($P<0.05$). Regression models are represented in equation 1- 4.

With increase in the depth of cut, amount of material gets deformed is increased which leads to the increase in cutting force. With increase in the feed rate, tool traverse speed against the work material increase, this in turn leads to increase in amount of material with time resulted in rise in cutting force.

3.4 Analysis of surface roughness

Figure 1 (d) depicts the interaction effects of surface roughness for Ti-multilayer coated tool. The effect of speed and feed rate are phenomenal in the study of surface roughness. Increase in feed rate resulted in increase in the surface roughness. Depth of cut is less influencing the surface roughness during machining. Increase in speed resulted in decrease in the surface roughness. Depth of cut and feed rate are contributing more in RSM results compared to speed.

Surface roughness is very sensible to variations in the feed rate and speed. With increase in the speed, contact between tool and material reduces which leads to lesser surface roughness. With increase in the feed rate, tool traverse speed against the work material increase, leads to increase in friction, resulted in higher surface roughness similar findings shown in Bouacha. et al. (2010).

Cutting force and surface roughness are optimized using the both the optimization techniques (0.2mm depth of cut, 625rpm speed and 0.093mm/rev feed rate). With the higher cutting speed there will more rotational torque in the material which reduce the cutting forces (Angadi et al., 2015). Depth of cut is kept at level 1 with the least depth of cut the amount of material deformed is minimal which in turn results the better surface roughness. Feed rate of 0.093mm/rev is ideal for achieving better roughness for the MDN431 material. Using Ti coated tool better surface and lesser cutting forces are observed which is due to reduced coefficient of friction in the multilayer Ti coatings, CoF results are as discussed in Badiger. et al. (2017).

3.5 Validation experiments

Equations 1-4 are used to predict the results for RSM design. Plot of experimental and predicted results are represented in Figure 2.

Plot of experimental and predicted results are found to be with least error and no significant deviation from the experimental results are observed. CoD of RSM design is close to 1, confirming the developed model is adequate. Validation of the developed regression models are represented in Table 4, and results are with negligible error.

Response surface methodology (CCRD)

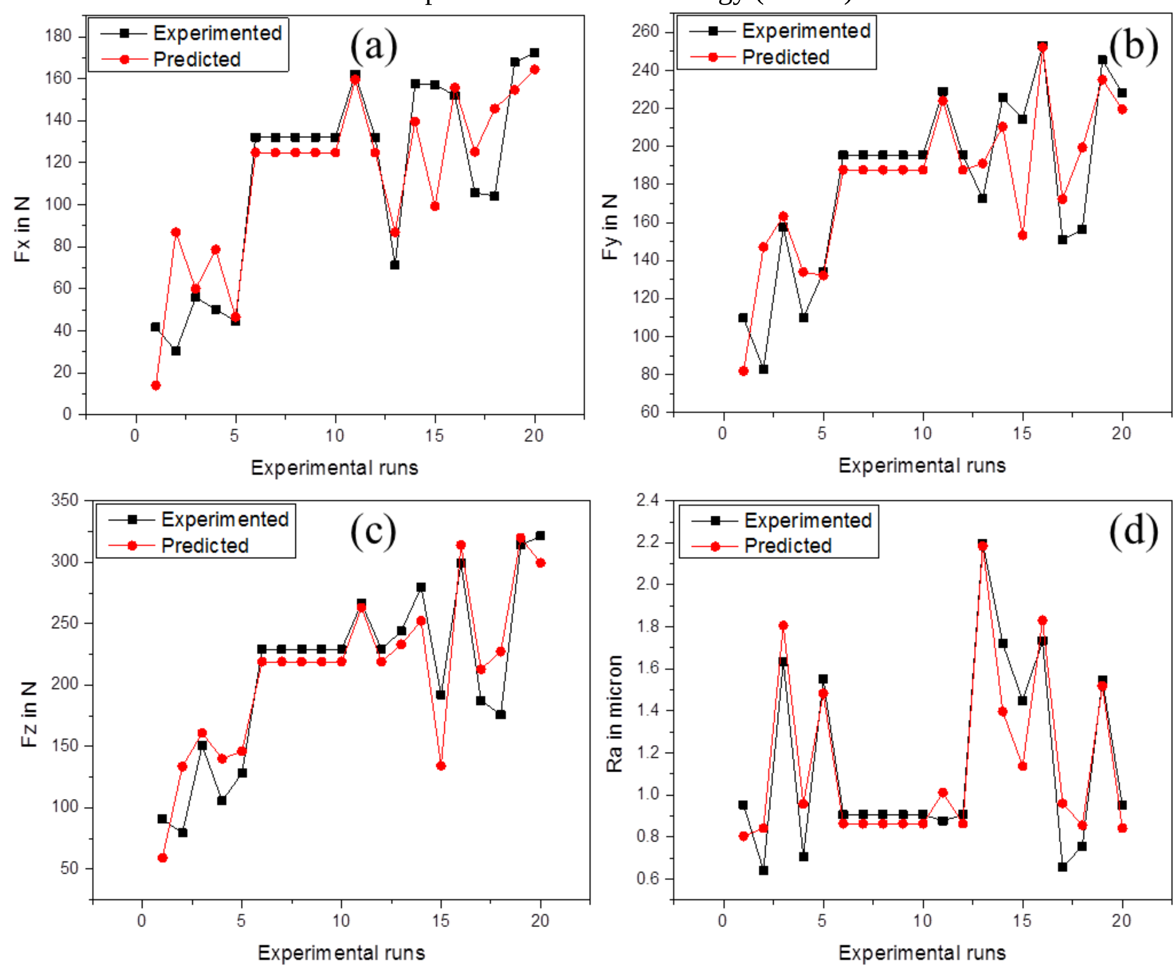

Fig. 2. Plots of experimental and predicted results for RSM analysis

4. CONCLUSIONS

Experimental investigation on the influence of Ti-multilayer coated tool has been presented. RSM CCRD designs are utilized for the analysis and validation of experiments. Regression models for cutting forces and surface roughness are developed for response surface methodology central composite rotatable design. Optimum machining condition is obtained with the combination of 0.2mm depth of cut, 625rpm speed and 0.093mm/rev feed rate for least cutting force and surface roughness. CoD (R^2) central composite rotatable design is close to 1, confirms the developed model is adequate. Validation experiments shown that the models presented can be used for the selection, design and optimization of machine tool, cutting tool in the process planning. Using Ti coated tool better surface and lesser cutting forces are obtained.

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6. REFERENCES

1. Angadi, S.B. et al., (2015). *Experimental Investigations on Drilling Characteristics of Cenosphere Reinforced Epoxy Composites*, App. Mech. and Mat., 766-767, 801-811.

2. Badiger, P.V. et al., (2017). *Development and Characterization of Ti/TiC/TiN Coatings by Cathodic Arc Evaporation Technique*, Trans. Indian Inst. Met., 70(9), 2459-2464.

3. Badiger, R.I. et al., (2015). *Joining of Inconel-625 alloy through microwave hybrid heating and its characterization*, J. Manuf. Processes, 18, 117-123.

4. Bouacha, K. et al., (2010). *Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool*, Int. J. Refract. Met. Hard Mater, 28(3), 349-361.

5. Chinchanikar, S, and Choudhury, S.K., (2014). *Characteristic of Wear, Force and their Inter-relationship: In-process Monitoring of Tool within*

Different Phases of the Tool Life, Procedia Mater. Sci., 5, 1424-1433.
6. Davim, J.P. and Figueira, L., (2007). *Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques*, Materials & Design, 28(4), 1186-1191.
7. Dumpala, R. et al., (2013). *Growth and characterization of integrated nano- and microcrystalline dual layer composite diamond coatings on WC–Co substrates,* Int. J. Refract. Met. Hard Mater, 37, 127-133.
8. Gaitonde, V.N. et al., (2012). *Experimental studies on hole quality and machinability characteristics in drilling of unreinforced and reinforced polyamides,* J. Compos. Mater, 48(1), 21-36.
9. Garcí et al., (2013). *Mechanisms involved in the improvement of Inconel 718 machinability by laser assisted machining (LAM),* Int. J. Mach. Tools Manuf, 74, 19-28.
10. Hiremath, V. et al., (2016). *Influence of particle size on Cutting Forces and Surface Roughness in Machining of B4Cp-6061 Aluminium Matrix Composites*. Paper presented at the IOP Conference Series: Materials Science and Engineering, 114(1), p. 012041
11. Kadi, R.V. and Dundur, S.T., (2015). *Optimization of dry turning parameters on surface roughness and hardness of Austenitic Stainless steel (AISI316) by Taguchi Technique*, The Journal of Engineering and Fundamentals, 2(2), 30-41.
12.Kıvak, T., (2014). *Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts.* Measurement, (50), 19-28.
13. Qin, F. et al., (2009). *Delamination wear of nano-diamond coated cutting tools in composite machining*, Wear, 267(5-8), 991-995.
14. Sahoo, A.K. and Sahoo, B., (2012). *Experimental investigations on machinability aspects in finish hard turning of AISI 4340 steel using uncoated and multilayer coated carbide inserts,* Measurement, 45(8), 2153-2165.
15. Sahoo, A.K. and Sahoo, B., (2013). P*erformance studies of multilayer hard surface coatings (TiN/TiCN/Al2O3/TiN) of indexable carbide inserts in hard machining: Part-I (An experimental approach),* Measurement, 46(8), 2854-2867.
16. Sharman, A.R.C. et al., (2015). *The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718,* J. Mater. Process. Technol., 216, 123-132.
17. Sivaiah, P. and Chakradhar, D., (2017). *Experimental investigation on feasibility of cryogenic, MQL, wet and dry machining environments in turning of 17-4 PH stainless steel,* Mater. Manuf. Processes. In Press
18. Suresh, R. et al., (2012). *Machinability investigations on hardened AISI 4340 steel using coated carbide insert.* Int. J. Refract. Met. Hard Mater, 33, 75-86.
19. Wang, C. et al., (2014). *Design of an instrumented smart cutting tool and its implementation and application perspectives,* Smart Mater. Struct., 23(3), 035019.

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