Nano World Journal

https://doi.org/10.17756/nwj.2023-s4-009

Research Article

Open Access

Experimental Study on Cryogenically Treated Tungsten Carbide End Mill Cutter by Taguchi Method and Response Surface Methodology

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Received: September 15, 2023
Accepted: November 20, 2023
Published: November 23, 2023

Citation: Mukkoti VV, Thummala VSN, Kunta A, Ambati R, Godi M, et al. 2023. Experimental Study on Cryogenically Treated Tungsten Carbide End Mill Cutter by Taguchi Method and Response Surface Methodology. *NanoWorld J* 9(S4): S49-S54.

Published by United Scientific Group

Abstract

In this study, an effort is made to use response surface methodology (RSM) and the Taguchi approach to optimize the process variables in CNC (Computed numerical control) milling of P20 steel using cryogenically treated tungsten carbide (WC) cutting tools feed rate (FR), cutting speed (CS), depth of cut (DoC), and lowering temperatures are selected as input parameters for milling of P20 steel. The machinability of P20 steel is claimed to be affected by several levels of cryogenic treatment i.e., -110 °C, -150 °C, and -175 °C in this study. The most crucial performance indicators were cutting forces (CF), rate of material removal (MRR), surface roughness (Ra), tool wear rate (TWR), and power consumption (PC). RSM and Taguchi approaches were suggested to achieve the optimized results for the process's variables. Both methods' optimized solutions were compared and analyzed. It is seen from the comparison that there is no much deviation in results obtained from RSM and Taguchi methods. It is also observed that, Deep Cryogenically Treated (DCT) tool i.e., at -175 °C showed better results compared with the other two tools to improve the performance measures.

Keywords

Cryogenic treatment levels, Taguchi method, Tungsten carbide tools, Response surface methodology, Process parameters

Introduction

The CNC milling technology is widely utilized in manufacturing for a variety of commercial purposes. Therefore, during the past ten years, academics' interest in the CNC end milling method has grown significantly. Most tools used in machining were exposed to excessive random and high loads. Therefore, cutting tools must be able to withstand those high variable loads without deforming or wearing out too quickly [1-3].

Padmakumar and Dinakaran [4] studied on cryogenic treatment on WC tool material. He studied that due to cryogenic treatment there is a metallurgical changes happening in tool material. He observed that grain size is refining and phase changes are occurring due to cryogenic treatment. He reported that tool performance is improved by cryogenic treatment.

Ciretti et al. [5] proposed a model of 3D machining processes utilizing finite element methods. When the results of the simulation are contrasted with those of the experiment, it can be seen that they agree fairly well with the latter. Zhang et al. [6] examined the use of Taguchi design in order to maximize Ra during CNC milling. From the investigation, it is revealed that Taguchi design has successfully optimized process variables for responses like Ra. Karnan et al. [7] investigated to improve tool life by cryogenic treatment. In this the process parameters in dry turning were optimized using Taguchi gray relational analysis. They found that from the study that DCT tool enhanced the machining performance. Lee et al. [8] examined the effect of DCT on WC carbide cutting tool. Soaking duration in cryogenic treatment is considered to study the phase changes in the material. From the study they observed that the properties like hardness is strengthened at 6 h soaking duration and then reduced at 12 h. They also observed the grain growth behavior by scanning electron microscope analysis.

The CNC milling technique has broad variety of applications in the industrial industries, according to previous studies [9-10]. Researchers have also concentrated on nano layered formation in WC for nano coatings. Many of them studied on the nano coatings on cutting tool and its behavior. The TWR and cutting tool life increases with the nano coatings. By cryogenic treatment on nano-coated cutting tools has much impact [11-13]. There is a lot of scope in cryogenic treatment on nano-coated cutting tools [14-15].

According to the research on CNC end milling, little attention has been given for analyzing the impact of DCT soaking period when determining machining efficiency and optimizing the process when utilizing WC end mill blades. However, studies are only able to analyze the process variables and how they affect tool wear. There is very little research on cryogenic treatment, especially when soaking period is one of the process parameters [3-9]. Additionally, very little research has been done to examine how cryo-treatment affects the tool's micro-structural alterations. Therefore, it is crucial to offer a reliable model that enhances milling process efficiency by raising MRR and lowering unfavorable characteristics like PC, TWR, Ra, and CF.

Experimentation

Taguchi and RSM were utilized to generate the experiments. Three WC end mill cutter were purchased to machine P20 steel. Table 1 lists the machining parameters that were utilized. Analysis on the cause of reducing temperature on WC cutting tools during CNC milling is the primary goal of the experiment. Cryo-treatment setup is utilized from IISc Bangalore (Karnataka, India) shown in figure 1. Figure 2 and figure 3 depict tools that have been cryogenically treated and CNC milling operations.

Results and Discussion

RSM

The results of the experiment are shown in a table 2. The RSM method was used to analyze the experiment's results in order to find out how various parameters influence responses utilizing ANOVA (Analysis of variance) using a 0.05 level of significance. To maximize the efficiency of the CNC milling process, using the major desirability plots, an ideal set of machining parameters that influence performance metrics should be selected.

According to the experimental table, using a tool that had been treated with DCT at -175 °C increased MRR by 23.32% while reducing TWR, Ra, CF, PC, and other factors by 30.32%, 74.68%, 28.48%, and 13.37%, when compared with SCT tool. Table 3 displays the optimized process variables for

Table 1: Machining parameters used.

Parameters	Levels		
	1	2	3
FR (mm/tooth)	0.1	0.15	0.2
CS (m/min)	75	85	95
DoC (mm)	0.5	1	1.5
Lowering temp. (°C)	-110	-150	-175

Figure 1: Cryo-treatment setup at IISc Bangalore (Karnataka, India).

Figure 2: WC cutting tools utilized.

Figure 3: CNC milling operations.

Table 2: Experimentation results.

S. No.	A: CS	B: FR	C: DoC	D: LT	MRR	TWR	Ra	CF	PC
	(m/min)	(mm/tooth)	(mm)	(°C)	(mm^3/min)	(mm^3/min)	(microns)	(N)	(W)
1	75	0.15	1	-1	44325.6	46.7173	1.48	360	1390
2	85	0.2	1	-1	55300.4	50.63	1.5	410	1785
3	85	0.15	1.5	-1	64503.5	58.0591	1.78	405	1495
4	85	0.15	0.5	-1	54023.3	53.2911	1.3	379	1608
5	85	0.1	1	-1	47963.1	55.4008	1.2	385	1512
6	95	0.15	1	-1	60884.1	56.1814	1.15	415	1948
7	75	0.15	1	1	58843.8	26.097	0.68	265	1046
8	85	0.15	1.5	1	80326.2	40.0844	0.44	285	1295
9	85	0.1	1	1	63929.2	35.865	0.69	265	1205
10	85	0.2	1	1	80003.9	42.1941	0.58	285	1236
11	85	0.15	0.5	1	65460.1	29.5359	0.48	265	1152
12	95	0.15	1	1	78562.2	48.5232	0.36	295	1406
13	75	0.1	1	0	48131.3	44.3038	1.48	330	1069
14	75	0.15	0.5	0	50403.4	45.9198	1.35	315	1002
15	75	0.2	1	0	55124.5	51.4135	1.54	345	1185
16	75	0.15	1.5	0	49612	48.5232	1.6	350	1296
17	85	0.15	1	0	63605.1	50.5232	1.38	320	1402
18	85	0.15	1	0	63605.1	50.5232	1.38	320	1402
19	85	0.15	1	0	68605.1	50.5232	1.38	320	1402
20	85	0.1	0.5	0	52403.4	36.0844	0.72	305	1346
21	85	0.15	1	0	63605.1	50.5232	1.38	320	1402
22	85	0.2	1.5	0	84806.9	62.0717	1.45	375	1532
23	85	0.2	0.5	0	68219.7	58.7426	1.05	330	1420
24	85	0.15	1	0	63605.1	55.5232	1.58	320	1402
25	85	0.1	1.5	0	72085.8	68.2911	1.22	335	1386
26	95	0.2	1	0	72085.8	64.1814	1.25	365	1730
27	95	0.1	1	0	62757.1	58.962	0.85	350	1652
28	95	0.15	1.5	0	72583.3	72.346	1.15	385	1815
29	95	0.15	0.5	0	60884.1	52.3038	0.9	345	1590

Table 3: Optimum values for the process variables.

Process variables	Optimum values
CS	85.207
FR	0.16
DoC	1.141
Cryogenic soaking duration	3.000
MRR	89563.9
TWR	37.71
Ra	0.546
CF	281.374
PC	1247.792
Desirability	0.760

raising CNC milling performance metrics. The top combinations of the resulting machining variables are established. The solution's graph of desirability is shown in figure 4.

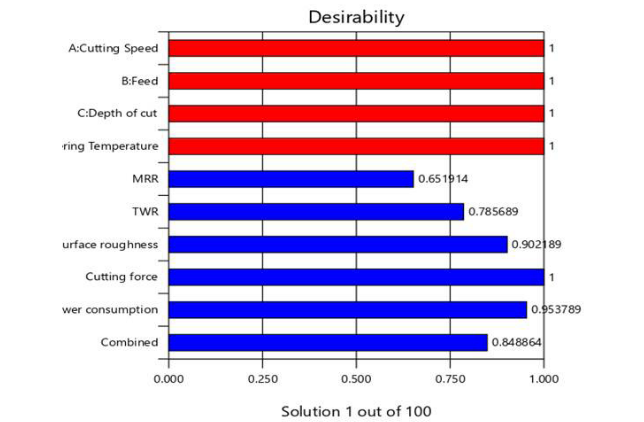


Figure 4: Desirability bar chart.

Taguchi method

The Taguchi method uses CS, FR, DoC, and reducing temperatures as inputs, and MRR, TWR, CF, and PC as outputs to determine the ideal conditions. L27 orthogonal array is selected for experimental runs. Experimental table is tabulated in table 4.

The MRR ANOVA is displayed in table 5. According to the ANOVA results, the most important factors affecting MRR, TWR, Ra, CF, and PC are CS, FR, DoC, and reducing temperature. The equations 1 to 5 obtained through regression analysis with respect to actual factors are shown below.

$$MRR = +96962.34 + 1539.43 \times A - 1.79 \times 10^4 \times B - 61315.32 \times C - 1.49 \times 10^4 \times D + 1296.52 \times A \times C + 1449.22 \times A \times D + 1.58 \times 10^4 \times B \times D + 9205.68 \times C \times D - 28.13 \times A^2 - 21851.69 \times C^2 \quad (1)$$

$TWR = +70.85 + 0.60 \times A - 120.79 \times B - 1.29 \times C - 56.49 \times D + 0.39 \times A \times C + 0.50 \times A \times D - 170.68 \times B \times C - 1.99 \times C \times$

Table 4: Experimentation results.

S. No.	CS	CF	DoC	Cryogenic soaking duration	MRR	TWR	Ra	CF	PC
	(m/min)	(mm/tooth)	(mm)	(h)	(mm^3/min)	(mm^3/min)	(microns)	(N)	(W)
1	85	0.20	1.50	0	84806.9	59.071	1.28	315	1396
2	85	0.15	1.00	0	63605.1	48.523	1.12	290	1432
3	85	0.15	1.50	1	76326.2	40.084	0.44	280	1272
4	85	0.10	0.50	0	42403.4	40.084	0.86	280	1372
5	85	0.15	0.50	-1	42403.4	63.291	1.45	314	1608
6	85	0.10	1.00	-1	38163.1	65.40	1.4	318	1512
7	85	0.20	1.00	-1	46643.8	50.633	1.68	335	1785
8	75	0.15	1.00	1	46643.8	21.097	0.68	278	1046
9	85	0.15	1.00	0	63605.1	48.523	1.12	290	1432
10	95	0.15	0.50	0	50884.1	44.304	0.78	275	1610
11	95	0.20	1.00	0	72085.8	61.181	1.02	320	1790
12	85	0.20	1.00	1	106009	42.194	0.58	294	1226
13	95	0.15	1.00	1	118730	48.523	0.36	275	1406
14	75	0.15	0.50	0	42403.4	36.92	1.38	276	1012
15	95	0.15	1.50	0	84806.9	64.346	0.95	285	1823
16	85	0.10	1.50	0	72085.8	63.291	1.12	285	1358
17	95	0.15	1.00	-1	50884.1	61.181	1.31	298	1948
18	85	0.10	1.00	1	64029.2	35.86	0.69	273	1205
19	75	0.20	1.00	0	55124.5	46.413	1.24	302	1218
20	85	0.15	0.50	1	50460.1	29.536	0.48	272	1172
21	75	0.15	1.00	-1	41131.3	90.717	1.48	313	1390
22	85	0.15	1.00	0	63605.1	48.523	1.25	290	1432
23	85	0.15	1.50	-1	50036	78.059	1.95	335	1752
24	85	0.15	1.00	0	63605.1	48.523	1.25	290	1432
25	75	0.10	1.00	0	41131.3	44.303	1.43	286	1098
26	75	0.15	1.50	0	49612	48.523	1.58	295	1176
27	95	0.10	1.00	0	62757.1	56.962	1.02	287	1685

Table 5: ANOVA for MRR.

Source	Sum of Squares	dof	Mean Square	F Value	p-value Prob > F	
Model	9.491E+009	10	9.491E+008	13.58	< 0.0001	Significant
A-CS	2.244E+009	1	2.244E+009	32.10	< 0.0001	
B-FR	6.798E+008	1	6.798E+008	9.72	0.0059	
C-DoC	1.702E+009	1	1.702E+009	24.34	0.0001	
D-Lowering temp.	3.102E+009	1	3.102E+009	44.37	< 0.0001	
AC	1.784E+008	1	1.784E+008	2.55	0.1276	
AD	9.714E+008	1	9.714E+008	13.89	0.0015	
BD	2.805E+008	1	2.805E+008	4.01	0.0604	
CD	8.311E+007	1	8.311E+007	1.19	0.2899	
A^2	5.116E+007	1	5.116E+007	0.73	0.4036	
C^2	2.235E+008	1	2.235E+008	3.20	0.0906	
Residual	1.258E+009	18	6.991E+007			
Lack of Fit	1.178E+009	14	8.417E+007	4.21	0.0876	not significant

$D - 5.9 \times 10 - 3 \times A^2 + 1025.88 \times B^2 + 3.85 \times C^2 + 1.50 \times D^2$ (2)

$Ra = -1.25 + 0.15 \times A + 4.79 \times B + 1.31 \times C + 0.52 \times D - 2.72 \times B \times D - 0.40 \times C \times D - 3.9 \times 10 - 3 \times A^2 + 9.86 \times B^2 - 0.20 \times C^2 - 0.03 \times D^2$ (3)

$CF = +645.55 - 2.73 \times A - 1885.82 \times B - 10.83 \times C - 99.11 \times D + 8.60 \times A \times B + 0.72 \times A \times D + 280.00 \times B \times C - 6.50 \times C \times D + 3598.86 \times B^2 + 8.37 \times D^2$ (4)

$PC = -250.18 + 36.58 \times A + 6215.24 \times B + 373.89 \times C + 389.41 \times D - 4.85 \times A \times D - 1254.00 \times B \times D - 9286.36 \times B^2 - 139.86 \times C^2$ (5)

It can be assessed that the general reliability of the regression model by comparing the value of p to a substantial threshold, with the most popular options being 0.01, 0.05, and 0.10. There is enough data to determine whether the regression model suits the results more effectively than a model with no predictor factors if the p-value falls below the 0.05 level.

Figure 5 shows the MRR variations surface plotted against CS vs feed. Table 6 compares the Taguchi technique and RSM optimized values, as well as the percentage variance between the parameter in each approach. Both strategies can be utilized to improve results; they produce results that are almost identical. By executing a number of process variables, validation tests were conducted with an accuracy level of 95%.

Micro-structural analysis

It is evident from figure 6, that the M12C (Co_6W_6C) - type carbide, which does not weaken the structure as much as the earlier type does, precipitated in the solid state following cryogenic treatment with minute grains dispersed across the matrix. Together with the bigger particles, these tiny particles create a matrix in the substance that is denser, more coherent, and far more durable. The thermal conductivity of the WC-Co material enhances as the size of the α-phase particles grows following cryogenic treatment. The ability of a material to dissipate heat is increased by the increase in thermal conductivity caused by cryogenic treatment.

Table 6: Comparison of RSM values with Taguchi method optimized parameter values.

Parameters	RSM values	Taguchi method values	% variation
Ra (mm)	0.5	0.527	0.02%
MRR (mm^3/min)	70663.075	70853.25	1.9%
TWR (mm^3/min)	35.996	38.25	2%
CF (N)	264.993	270.45	5%
PC (W)	1043.417	1044.52	1%

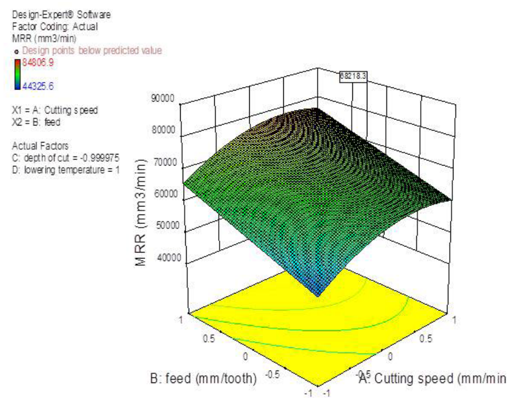
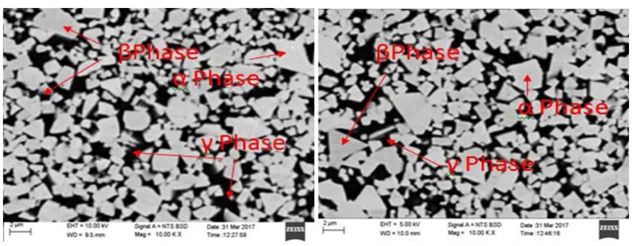


Figure 5: MRR variations surface plotted against CS vs feed.



(a) (b)

Figure 6: Micro-structure of WC carbide tools **(a)** SCT-110 °C and **(b)** DCT-175 °C.

Conclusions

This research aims to examine the effects of cryogenic treatment on WC end mill cutter when they are treated with a range of cryogenic temperatures while CNC milling of a P20 steel workpiece. RSM and Taguchi approaches were used to optimize the process parameters, and the outcomes were compared. The following conclusions can be drawn from the experimentation and results analysis:

- It is found from the results that, when compared with other treated tools, DCT is showed better performance in machining of P20 steel material.
- In comparison to using an SCT-treated tool, it was shown that utilizing a DCT tool led to an increase in MRR of 24.53%, a decrease in TWR, Ra, CF, and PC of 30.90%, 75.28%, 29.62%, and 13.37%, respectively.
- From scanning electron microscope analysis, it was seen that surface texture is increased on workpiece with DCT tool compared with other treated tools.
- It is observed from the analysis that DCT cutting tools are preferable for milling P20 steel workpieces in order to achieve increased MRR, low TWR, Ra, CF, and PC compared with other treated tools.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Mohanty CP, Mahapatra SS, Singh MR. 2016. A particle swarm approach for multi-objective optimization of electrical discharge machining process. *J Intell Manuf* 27: 1171-1190. https://doi.org/10.1007/s10845-014-0942-3
2. Mukkoti VV, Sankaraiah G, Yohan M. 2017. Performance evaluation of deep cryogenic treated tools at different temperatures in CNC milling. *ARPN J Eng Appl Sci* 12(24): 762-7273.
3. Mukkoti VV, Sankaraiah G, Yohan M. 2018. Effect of cryogenic treatment of tungsten carbide tools on cutting force and power consumption in CNC milling process. *Prod Manuf Res* 6(1): 149-170. https://doi.org/10.1080/21693277.2018.1436011
4. Padmakumar M, Dinakaran D. 2021. A review on cryogenic treatment of tungsten carbide (WC-Co) tool material. *Mater Manuf Process* 36(6): 637-659. https://doi.org/10.1080/10426914.2020.1843668
5. Ceretti E, Lazzaroni C, Menegardo L, Altan T. 2000. Turning simulations using a three-dimensional FEM code. *J Mater Process Technol* 98(1): 99-103. https://doi.org/10.1016/S0924-0136(99)00310-6
6. Zhang JZ, Chen JC, Kirby ED. 2007. Surface roughness optimization in an end-milling operation using the Taguchi design method. *J Mater Process Technol* 184(1-3): 233-239. https://doi.org/10.1016/j.jmatprotec.2006.11.029

7. Karnan B, Kuppusamy A, Latchoumi TP, Banerjee A, Sinha A, et al. 2022. Multi-response optimization of turning parameters for cryogenically treated and tempered WC-Co inserts. *J Inst Eng India Ser D* 103(1): 263-274. https://doi.org/10.1007/s40033-021-00321-x

8. Lee JH, Hong SK, Park HK. 2021. Effects of deep cryogenic treatment for tungsten carbide-iron cemented carbide. *Int J Refract Met Hard Mater* 100: 105649. https://doi.org/10.1016/j.ijrmhm.2021.105649

9. Mukkoti VV, Mohanty CP, Gandla S, Sarkar P, Rao PS. 2020. Optimization of process parameters in CNC milling of P20 steel by cryo-treated tungsten carbide tools using NSGA-II. *Prod Manuf Res* 8(1): 291-312. https://doi.org/10.1080/21693277.2020.1790436

10. Mahendran R, Rajkumar P, Raj LN, Karthikeyan S, Rajeshkumar L. 2021. Effect of deep cryogenic treatment on tool life of multilayer coated carbide inserts by shoulder milling of EN8 steel. *J Braz Soc Mech Sci Eng* 43(8): 378. https://doi.org/10.1007/s40430-021-03100-7

11. Vardhan VM, Renita KR, Kumar SH. 2023. Hand gestures controlled intelligent wheelchair with device switch. *NanoWorld J* 9(S1): S1-S5. https://doi.org/10.17756/nwj.2023-s1-001

12. Racz AS, Kun P, Kerner Z, Fogarassy Z, Menyhard M. 2023. Tungsten carbide nanolayer formation by ion beam mixing with argon and xenon ions for applications as protective coatings. *ACS Appl Nano Mater* 6(5): 3816-3824. https://doi.org/10.1021/acsanm.2c05505

13. Gowthami V, Sowjanya B, Kumar MN, Vangalapati M. 2023. Synthesized MgO/chitosan nanocomposite: it's application for the removal of dicofol and optimization by Box Benhken design. *NanoWorld J* 9(1): 1-7. https://doi.org/ 10.17756/nwj.2023-110

14. Amini K, Akhbarizadeh A, Javadpour S. 2012. Effect of deep cryogenic treatment on the formation of nano-sized carbides and the wear behavior of D2 tool steel. *Int J Min Metall Mater* 19: 795-799. https://doi.org/10.1007/s12613-012-0630-2

15. Ghosh S, Rao PV. 2019. Comparison between sustainable cryogenic techniques and nano-MQL cooling mode in turning of nickel-based alloy. *J Clean Prod* 231: 1036-1049. https://doi.org/10.1016/j.jclepro.2019.05.196