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Optimization of process parameters in CNC milling of P20 steel by cryo-treated tungsten carbide tools using NSGA-II

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ABSTRACT

This article proposes an extensive experimental and microstructural analysis to study the consequences of deep cryogenic treatment (DCT) soaking duration on tungsten carbide end mill cutter on the machinability of P20 mold steel. A Box-Behnken design of response surface methodology (RSM) is utilized to collect data for the study. Cutting speed, feed rate, depth of cut and milling cutters subjected to various soaking durations are taken as important process variables which are a function of performance measures viz. tool wear rate (TWR), material removal rate (MRR) and surface roughness (R_a). It is observed that cutting speed, feed, depth of cut and cryogenic treatment exhibit a considerable effect on performance measures. In the present study, NSGA-II multi-objective optimization technique is used to obtain the optimal process parameters of end milling process to enhance the productivity of the process. For this purpose, the developed RSM model is coupled with NSGA-II in MATLAB.

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KEYWORDS
Deep Cryogenic Treatment; Soaking Duration; NSGA-II; Regression Analysis; Microstructural Analysis; P20 steel

1. Introduction

CNC milling machines find extensive application in the manufacturing industry. CNC end milling can make peripheral or slot cuts or specific features such as profile, slot, pocket or even a complex surface contour (Kondayya & Gopala Krishna, 2012). While machining hard materials in the milling process, tungsten carbide end mill cutting tools are commonly used by the manufacturing units (Yong et al., 2007). Tungsten carbides are of high wear-resistant refractory materials wherein the rigid tungsten carbide particles are established collectively by the soft and ductile metal like cobalt. Tungsten carbides are mostly utilized in industrial applications. Their importance is by far inferable from their excellent wear resistance that makes them good for cutting tools, rock-drilling, metal-forming process. In CNC milling process, tungsten carbide end milling cutting tool material is generally utilized to machine high strength to weight ratio and toughened materials. While machining, the majority of tools are exposed to greatly higher and variable loads. Hence, cutting tools should resist those high fluctuating loads without

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undergoing deformation or excessive wear for a longer duration. The heat produced in the machining zone makes the cutting tool material soften which frequently results in fast tool wear, and consequently shortens tool life (Wang et al., 2017). High erosion of tool not only causes interruption during machining but also severely affects the economic aspects of the machining process by raising the cost of the tool. Therefore, the cutting tool life plays a vital role in every machining operation and hence is an important aspect for enhancing the productivity of the manufacturing processes.

Nowadays to enhance the tool life, cryogenic treatment, a substitute for normal heat treatment process is being applied extensively to enhance the productivity of different machining operations. Cryogenic treatment has a wide range of applications from industrial tooling to the improvement of musical signal transmission (Cajner et al., 2008; Giasin et al., 2016; Sartori et al., 2016). The cryogenic treatment brings some noteworthy improvement to material properties such as refining grain structure and enhancing the mechanical properties viz. thermal conductivity and microhardness, etc. (Arockia Jaswin & Mohan Lal, 2010; Cajner et al., 2008; Chen-hui et al., 2015; Dieringa, 2017; Giasin et al., 2016; Junji et al., 2016; Nalbant & Yildiz, 2011; Podgornik et al., 2016; Sartori et al., 2016; Sobotova et al., 2016; Swamini et al., 2015; Wang et al., 2017; Yang et al., 2016). The objective of cryogenic treatment is to convert austenite to martensite and increase the structure hardness. Austenite (a soft form of iron) is produced during the quenching stage of material production, which is a solid solution of iron and carbon. Austenite is a poor and adverse phase because in this phase molecular interfaces are not arranged properly. At the point when the material is cryo-treated, the austenite phase is gradually changed into a very composed grain structure called martensite. Martensite phase is the harder material which has high wear resistance which is exceptionally alluring in carbon steels. In addition to this, another advantage of cryogenic treatment is the increase in the capacity of heat dissipation in the material due to increased thermal conductivity. Due to cryogenic treatment, thermal conductivity is increased owing to refined and closely packed grains.

The input parameters involved in cryogenic treatment are soaking duration, lowering temperature, cooling and heating rates, quenching and tempering processes, etc. Many studies reported that in deep cryogenic treatment (DCT) soaking duration is an influential parameter than lowering temperature (Arockia Jaswin & Mohan Lal, 2010; Cajner et al., 2008; Chen-hui et al., 2015; Dieringa, 2017; Giasin et al., 2016; Junji et al., 2016; Nalbant & Yildiz, 2011; Podgornik et al., 2016; Sartori et al., 2016; Sobotova et al., 2016; Swamini et al., 2015; Wang et al., 2017; Yang et al., 2016). However, the effect of soaking duration on machining performance of CNC milling process is extremely rare in the literature. In the last decade, few researchers have attempted to incorporate cryogenic cooling during machining by using liquid nitrogen as a coolant on to the machining zone (Khan & Mirghani Ahmed, 2008; Chetan & Rao, 2017; Dhar et al., 2002; Kalyan Kumar & Choudhury, 2008; Shokrani et al., 2016). However, they concluded that with liquid nitrogen as coolant has no remarkable advantage in tool life and surface morphology over dry machining. Furthermore, when tool material will be in direct contact with liquid nitrogen the tool becomes brittle, and hence at higher speeds, it gets microcracks and flank wear occurs during machining (Chetan & Rao, 2017). Recently, DCT has resulted in a successful application to reduce tool wear for machining different materials in CNC turning process (Chetan & Rao, 2017; Cicek et al., 2013; Dhar et al., 2002; Gill et al., 2011;

Kalyan Kumar & Choudhury, 2008; Ozbek et al., 2014; Seah et al., 2003; Singh et al., 2011; Reddy et al., 2009; Vadivel & Rudramoorthy, 2009). However, as far as CNC end milling process is concerned a limited number of studies have been reported until now. Several studies aim to achieve an optimal level of machining parameters for CNC milling process by the application of artificial intelligence (AI) techniques viz. genetic algorithm (GA), artificial neural network (ANN), fuzzy logic, etc. (Arokiadass, 2015; Zhang et al., 2016; Datta & Kalyanmoy Deb, 2009; Deb, 2002; Jie et al., 2013; Jun et al., 2014; Sheng et al., 2016; Sreenivasulu, 2013). Most researchers have optimized commonly used input parameters like cutting speed, feed rate, depth of cut, etc. to achieve improved machining efficiency. However, a minimal number of studies have been reported till now for achieving an optimal level of machining parameters by considering soaking duration in cryogenic treatment as one of the process parameters.

In view of this, the present study proposes a novel approach by experimental investigating on DCT of tungsten carbide cutting tools subjected to various cryogenic soaking durations for machining of P20 steel material in the CNC end milling process. The efficiency of the machining process is assessed in terms of tool wear rate (TWR), material removal rate (MRR) and surface roughness (R_a) in CNC milling processes which are a function of decision variables viz. cutting speed, feed rate, depth of cut and soaking duration. Scanning electron microscope (SEM) study is performed to know any possible changes occurred in the microstructure during DCT for the treated and untreated tools. Analysis of variance (ANOVA) is carried out to recognize the significant input parameters. Regression analysis is carried out to relate process variables with the responses. In the end, a non-dominated sorting genetic algorithm-II (NSGA-II) is proposed to obtain Pareto optimum solutions.

2. Literature survey

CNC milling process is extensively used in manufacturing industries for various industrial applications. Therefore, in the last decade, CNC end milling process has emerged as one the major topic of research interest by the researchers. To enhance the productivity of the process numerous studies reported until now by the researchers have been summarized in the following lines. Yong et al. (2007) studied the consequences of DCT and untreated tungsten carbide tool inserts while machining medium carbon steel work material in CNC milling. The study revealed that cryogenically treated tungsten carbide inserts can enhance the tool life by 28.9–38.6% in comparison with untreated tool inserts. Nalbant and Yildiz (2011) studied the effect of cryogenic machining on resultant cutting forces in CNC milling of AISI 304 stainless steel material experimentally by using liquid nitrogen as a coolant. The study revealed that by using liquid nitrogen as a coolant by spraying it to the machining zone has no much effect over dry milling operation. Shokrani et al. (2016) analyzed the effects of cryogenic machining using liquid nitrogen on surface integrity of Ti-6Al-4V titanium alloy workpiece in CNC end milling operations. The study showed that cryogenic cooling had improved in surface quality by 39% and 31% when compared with flood and dry cooling methods. Thamizhmanii and Mohd Nagib (2011) analyzed the tool behavior of DCT and untreated PVD inserts in the CNC milling process on Inconel 718 material. The analysis revealed that cryogenically treated PVD inserts showed better results in terms of tool life and flank wear than untreated inserts. Nirmal Kalsi et al. (2010) analyzed the effect of DCT on different types of steel and other materials. It is observed that cryogenic treatment of materials has a noteworthy change in their properties like wear resistance, toughness, hardness, reduced residual stresses, fatigue resistance and better thermal conductivity.

In addition to above-discussed studies, few more experimental studies reported which employs statistical design of experiment approaches viz. Taguchi grey relational analysis and RSM to locate the best machining state to improve the productivity of the process (Routara et al., 2009; Oktem et al., 2005; Pang et al., 2014; Sahoo & Sahoo, 2013). Zhang et al. (2007) studied the application of Taguchi design to optimize the R_a in CNC milling process. The analysis showed that Taguchi design was successful in optimizing process parameters for the response. Maiyar et al. (2013) studied the optimization of end milling process parameters for machining Inconel 718 super alloy material using Taguchi grey relational analysis. The results showed that machining performance in end milling process has been improved effectively using grey relational analysis. But these statistical techniques are not satisfactory to obtain the complex relationship between influencing variables and output responses and the solutions obtained from these techniques are limited to a few applications (Kondayya & Gopala Krishna, 2012). Hence, there is a need for a multi-objective optimization method to achieve best solutions to the problem. Extensive study is needed to optimize the process parameters which are functions of decision variables viz. tool life, R_a and MRR to enhance the machining efficiency.

To overcome the drawback of the above mentioned statistical methods, recently many nature inspired algorithms are applied to optimize the machining parameter using non-traditional optimization techniques viz. GA, NSGA-II, particle swarm optimization (PSO) (Arokiadass, 2015; Zhang et al., 2016; Datta & Kalyanmoy Deb, 2009; Deb, 2002; Jie et al., 2013; Jun et al., 2014; Mohanty et al., 2014; Padhee et al., 2012; Sheng et al., 2016). However, applications of those approaches are mostly limited to performance measures like MRR, R_a, TWR, etc. Less effort has been made to achieve the optimized machining conditions for simultaneous optimization of performance measures and achieving Pareto optimal solutions. In addition to this mostly past study report optimized process condition for commonly used variables viz. cutting speed, feed, depth of cut, nose radius, etc. Therefore, there exists a vital need to propose the optimal process condition for the CNC end milling process considering a new process variable like cryogenic treatment soaking duration as it may enhance the productivity of the process. This invites a generation of a multi objective optimization problem in which a large number of non-dominated solutions have to be generated using a robust approach like GA under consideration.

The literature on CNC end milling reports, minimal effort has been paid to analyze the outcome of DCT soaking duration for evaluating the machining efficiency and for process optimization using tungsten carbide end mill cutters. Few studies report the application of DCT to enhance the tool life (Arockia Jaswin & Mohan Lal, 2010; Nalbant & Yildiz, 2011). However, their application limited to a number of single objectives like tool wear and flank wear, etc. It is also observed that minimal effort has been made to study the microstructural changes occurring in the tool material during cryogenic treatment. Hence, a vital requisite of proposing an efficient technological model is prevailing in CNC end milling machining which can enhance the productivity of the process by reducing the non-beneficial attributes viz. TWR and R_a and enhance the beneficial attributes like MRR. From the literature, it is also found that the soaking period has substantial effect (Nirmal Kalsi et al. 2010; Arockia Jaswin and Mohan Lal 2010) as compared to cooling rate, soaking temperature and tempering temperature in the enhancement of various properties like tensile strength, hardness and wear resistance. It was observed by Ozbek et al. (2014) and Arockia Jaswin and Mohan Lal (2010) that a soaking period beyond 36 h did not improve material properties considerably, hence, in the present study, 36 h was taken as upper limit of time period for soaking.

In this article, the CNC end milling experiments were carried out on vertical CNC milling machine. Tungsten carbide end milling cutters were treated with DCT for the different soaking duration. The microstructural analysis was conducted on DCT tools to analyze the changes in the grain structure by means of SEM. ANOVA is performed to find significant process parameters. Regression analysis is used to relate the process variables cutting speed, feed, depth of cut and cryogenic soaking duration with the responses MRR, TWR and R_a. A multi-objective optimization technique, i.e. NSGA-II is used to achieve the Pareto optimal set of solutions (Mohanty et al., 2014; Padhee et al., 2012).

3. Multi-objective optimization

Multi-objective evolutionary algorithms (MOEAs) are optimization methods that make use of the characteristics of the multipoint search of EAs and can obtain Pareto optimal solutions at the same time. GA is standout among the most popular MOEA; a natural method of progression with prominence on reproduction and the survival of the fittest. GA simulates the survival of the fittest among individuals over a successive generation to solve the problem. The individuals in the population are then made to experience a process of evolution. First, a preliminary population is arbitrarily created; the GA has three operators:

(a) Selection operator which compares to survival of the fittest;
(b) Crossover operator which resembles mating between individuals;
(c) Mutation operator represents arbitrary modifications.

These operators provide the search way toward a GA. The flow chart of GA is shown in Figure 1.

GA shows improved performance as compared to the conventional optimization techniques due to their robustness, independency of gradient information and use of inherent parallelism in searching the design space. In comparison to GA, the NSGA-II technique is more elitist, computational inexpensive, less complex and faster for multi-objective optimization. Therefore, in the present study, NSGA-II multi-objective optimization technique is applied to obtain the optimal process parameters of end milling process. For this purpose, the developed RSM model is coupled with NSGA-II in MATLAB.

NSGA II is an MOEAs derived from non-dominated sorting (Datta & Kalyanmoy Deb, 2009; Deb, 2002). To find the non-dominated set of solutions; this algorithm utilizes elitist non-dominated sorting. Constrained multi-objective optimization problems are handled by this algorithm through binary codes and actual parameter. Here, variables are coded by a suitable objective function. Once a definite number of generations are completed, this algorithm produces the non-dominated solution set out of the total population. The non-dominated solution set, i.e. the Pareto-front solution set is obtained from the convergence

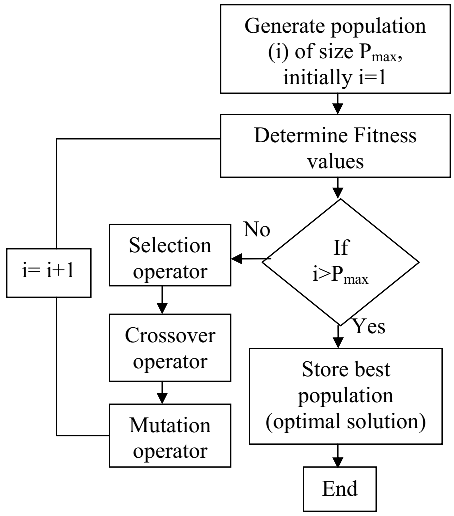


Figure 1. Genetic algorithm flow chart.

of the algorithm. Based on ranking and crowding distance, with the help of crowded-comparison operator optimal solution set is selected. NSGA-II is used to obtain a Pareto-optimal front to solve the three objective optimization problems by considering the function as two objective problems neglecting one objective in each run. A local search strategy is recommended from each obtained Pareto points in order to get a better solution in the study.

4. Experimental procedure

4.1. Experimental design

The experimental runs are designed according to Box Behnken design of response surface methodology (RSM). By using RSM, the effect of factors and their possible interactions can be studied and predictive equations can be generated and statistically validated. In general, a model of second-order shown in Equation (1) is employed in RSM (Mohanty et al., 2014).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} X_i X_j + \varepsilon \tag{1}$$

where Y is the output response, X_is are process parameters, X_{2i} and X_iX_j are the square and interaction terms of parameters respectively. β_0, β_i, β_{ii} and β_{ij} are the unknown regression coefficients and ε is the error.

4.2. Cutting tools used

The commercially available tungsten carbide end mill cutter with 12 mm diameter, 40 mm long (ISO specification) with four flutes was procured as recommended by tool supplier for machining of P20 steel work piece with dimensions 200 × 200 × 12 mm. The chemical composition of P20 steel is carbon 0.28–0.4%, chromium 1.4–2%, iron balance, manganese 0.6–1%, molybdenum 0.3–0.55%, silicon 0.2–0.8%, sulphur 0.03 % (max).

Three different tungsten carbide end mill cutters; untreated (UT) and DCT with different soaking durations were obtained. Cutting tools have been subjected to DCT in which they were cryogenically treated in the indigenously developed cryogenic treatment system for 24 h and 36 h at −175°C with 5 h of cooling and 9 h of warm up to room temperature are shown in Figure 2. The entire cryogenic treatment process took nearly 38 h consuming nearly 500 liters of liquid nitrogen. The details of the cryo-treatment system in Figure 3(a) are discussed below.

4.3. Cryogenic treatment system

The cryogenic treatment system incorporates mainly a cylindrical cryogenic treatment unit made out stainless steel SS304. It has a supplementary liquid nitrogen delivery system to deliver a controlled amount of pressurized liquid nitrogen to the chamber to maintain the soaking period, the rate of cooling and warm up period. The controlled

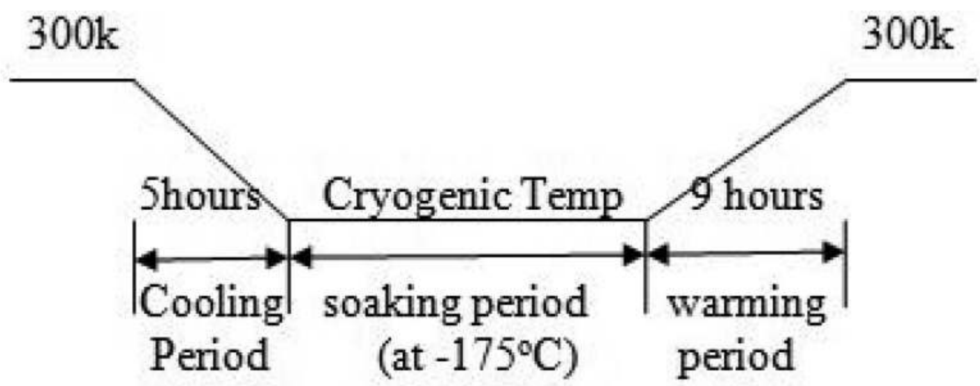
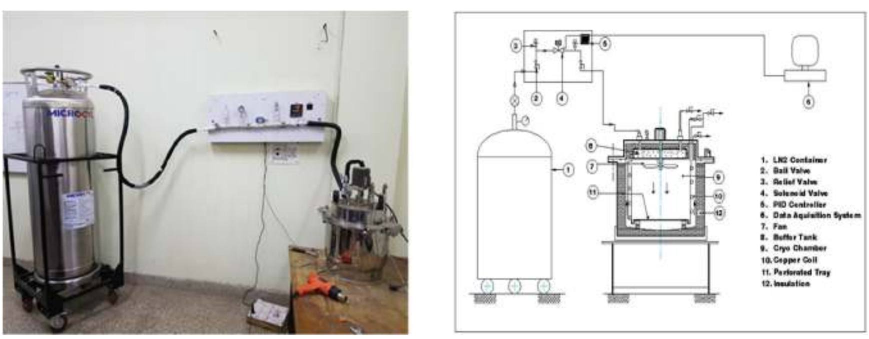


Figure 2. Cryo-treatment cycle.



(a) (b)

Figure 3. (a) Cryo-treatment system. (b) Schematic process of cryo-treatment system.

liquid nitrogen delivery to the chamber is having a solenoid valve connected to a proportional integral derivative (PID) controller shown in Figure 3(b).

The liquid nitrogen supply is regulated by the solenoid valve controlled by a PID controller with predetermined values. The temperatures of the work material are measured using platinum resistance temperature detectors (RTD). The temperature information of the samples read by PID over the period of the cryogenic treatment cycle is stored incessantly using a data acquisition system (Nadig et al., 2010).

4.4. Machining parameters

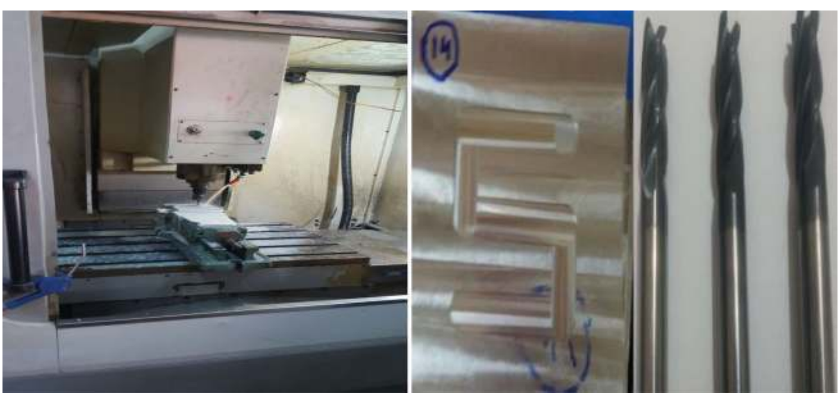
The machining parameters used are shown in Table 1.

4.5. Experimental process

The main aim of the machining test is to analyze the effect of DCT tungsten carbide end mill cutter on CNC milling process. End milling experiments were performed on the vertical CNC milling machine at Central Institute of Tool Design (CITD), Hyderabad as shown in Figure 4(a). The boron-based water-soluble oil is used as a coolant during machining. The P20 steel work material and tungsten carbide end mill cutters used in the experiment are shown in Figure 4(b). Twenty-nine experiments were conducted based on Box-Behnken design of RSM as shown in Table 2. Each experimental run is continued for 20 min and the time has been recorded with a stopwatch. High precision electronic weighing a machine with an accuracy of 0.001 g was used to measure the weights of the

Table 1. Machining parameters used.

	Levels		
Control parameters	Level 1	Level 2	Level 3
Cutting speed (m/min)	75	85	95
Feed (mm/tooth)	0.1	0.15	0.5
Axial depth of cut (mm)	0.5	1	1.5
Cryogenic soaking duration (h)	1 (0 h)	2 (24 h)	3 (36 h)



(a) (b)

Figure 4. (a) Machining operation in CNC milling. (b) Work material and different cutting tools.

Table 2. Experimental results.

S. No.	Cutting speed (m/min)	Feed (mm/tooth)	Depth of cut (mm)	Cryogenic soaking duration (h)	MRR (mm^3/min)	TWR (mm^3/min)	R_a (microns)
1	85	0.20	1.50	2	84,806.9	59.071	1.28
2	85	0.15	1.00	2	63,605.1	48.523	1.12
3	85	0.15	1.50	3	76,326.2	40.084	0.44
4	85	0.10	0.50	2	42,403.4	40.084	0.86
5	85	0.15	0.50	1	42,403.4	63.291	1.45
6	85	0.10	1.00	1	38,163.1	65.40	1.4
7	85	0.20	1.00	1	46,643.8	50.633	1.68
8	75	0.15	1.00	3	46,643.8	21.097	0.68
9	85	0.15	1.00	2	63,605.1	48.523	1.12
10	95	0.15	0.50	2	50,884.1	44.304	0.78
11	95	0.20	1.00	2	72,085.8	61.181	1.02
12	85	0.20	1.00	3	106,009	42.194	0.58
13	95	0.15	1.00	3	118,730	48.523	0.36
14	75	0.15	0.50	2	42,403.4	36.92	1.38
15	95	0.15	1.50	2	84,806.9	64.346	0.95
16	85	0.10	1.50	2	72,085.8	63.291	1.12
17	95	0.15	1.00	1	50,884.1	61.181	1.31
18	85	0.10	1.00	3	64,029.2	35.86	0.69
19	75	0.20	1.00	2	55,124.5	46.413	1.24
20	85	0.15	0.50	3	50,460.1	29.536	0.48
21	75	0.15	1.00	1	41,131.3	90.717	1.48
22	85	0.15	1.00	2	63,605.1	48.523	1.25
23	85	0.15	1.50	1	50,036	78.059	1.95
24	85	0.15	1.00	2	63,605.1	48.523	1.25
25	75	0.10	1.00	2	41,131.3	44.303	1.43
26	75	0.15	1.50	2	49,612	48.523	1.58
27	95	0.10	1.00	2	62,757.1	56.962	1.02
28	85	0.20	0.50	2	46,219.7	52.742	0.98
29	85	0.15	1.00	2	63,605.1	48.523	0.85

workpiece and cutting tool before and after machining. The weight of cutting tool and work piece material before and after machining is noted to calculate MRR and TWR using Equations (2) and (3).

$$TWR = 1000 * \Delta W_T/(\rho * T) \tag{2}$$

$$MRR = 1000 * \Delta W_w/(\rho * T) \tag{3}$$

where ΔW_w = change in weight of workpiece (grams), ρ = density (kg/m^3), T = machining time (minutes).

A similar type of calculation has been reported elsewhere (Mohanty et al., 2014). The R_a of the machined work material surface is measured by a Taylor Hobson Surtronic 3^+ stylus instrument as shown in Figure 5. In the forward direction, average R_a values of the work piece are noted, repeated for four times and an average of four readings of R_a values are tabulated.

4.6. Analysis of variance

ANOVA is a statistical analysis tool that separates the total variability found within a dataset into two components. ANOVA is a collection of statistical models and their associated estimation procedures used to analyze the differences among groups in a sample. Table 3 shows the ANOVA table for MRR after removal of insignificant parameters. The parameters

Figure 5. Taylor Hobson surface roughness testing equipment.

Table 3. ANOVA for MRR.

Source	Sum of squares	DOF	Mean square	*F* value	*p* value Prob. > *F*	% Contribution
A – cutting speed	2.244E+009	1	2.244E+009	32.10	<0.0001	23.36
B – feed	6.798E+008	1	6.798E+008	9.72	0.0059	7.14
C – depth of cut	1.702E+009	1	1.702E+009	24.34	0.0001	17.88
D – cryogenic soaking duration	3.102E+009	1	3.102E+009	44.37	<0.0001	32.58
AC	1.784E+008	1	1.784E+008	2.55	0.1276	1.87
AD	9.714E+008	1	9.714E+008	13.89	0.0015	10.20
BD	2.805E+008	1	2.805E+008	4.01	0.0604	2.95
CD	8.311E+007	1	8.311E+007	1.19	0.2899	0.87
A^2	5.116E+007	1	5.116E+007	0.73	0.4036	0.54
C^2	2.235E+008	1	2.235E+008	3.20	0.0906	2.34
Total	9.52E+09					100

DOF: degrees of freedom.

cutting speed, depth of cut, feed, cryogenic soaking duration, and interaction terms cutting speed × cryogenic soaking duration, feed × cryogenic soaking duration are found to be the most significant parameters. Similarly, ANOVA for TWR in Table 4 shows that cutting speed, depth of cut, cryogenic soaking duration, interaction term cutting speed × cryogenic soaking duration are found to be the most significant parameters. ANOVA for R_a in Table 5 shows that cutting speed, feed, depth of cut, cryogenic soaking duration are found to be the most significant parameters. The coefficient of determination (R^2) and adjusted R^2 values are 88.29% and 81.79% for MRR, 97.55% and 95.72% for TWR, 97.19% and 95.62% for R_a, respectively. It is observed that lack of fit is insignificant to all the output responses.

5. Results and discussion

The experimental results are shown in Table 2. The analysis was done on the experimental data collected based on Box-Behnken design to establish the connection of

Table 4. ANOVA for TWR.

Source	Sum of squares	DOF	Mean square	*F* value	*p* value Prob. > *F*	% Contribution
A – cutting speed	638.36	1	638.36	90.13	<0.0001	14.08
B – feed	62.24	1	62.24	8.79	0.0091	1.37
C – depth of cut	623.49	1	623.49	88.04	<0.0001	13.75
D – cryogenic soaking duration	2944.80	1	2944.80	415.80	<0.0001	64.97
AC	17.80	1	17.80	2.51	0.1324	0.39
AD	80.66	1	80.66	11.39	0.0039	1.78
BC	71.21	1	71.21	10.06	0.0059	1.57
CD	4.45	1	4.45	0.63	0.4395	0.098
A^2	2.95	1	2.95	0.42	0.5278	0.065
B^2	50.29	1	50.29	7.10	0.0170	1.11
C^2	8.93	1	8.93	1.26	0.2781	0.19
D^2	13.91	1	13.91	1.96	0.1802	0.306
Pure error	12.80	4	3.20			0.282
Total	4531.89					

Table 5. ANOVA for surface roughness.

Source	Sum of squares	DOF	Mean square	*F* value	*p* value Prob. > *F*	% Contribution
A – cutting speed	0.55	1	0.55	78.74	<0.0001	12.68
B – feed	0.11	1	0.11	15.89	0.0009	2.53
C – depth of cut	0.14	1	0.14	20.62	0.0003	3.23
D – cryogenic soaking duration	3.27	1	3.27	470.84	<0.0001	75.41
BD	0.087	1	0.087	12.55	0.0023	2.00
CD	0.13	1	0.13	18.17	0.0005	3.00
A^2	0.011	1	0.011	1.60	0.2223	0.25
B^2	4.027E-003	1	4.027E-003	0.58	0.4559	0.09
C^2	0.010	1	0.010	1.50	0.2361	0.23
D^2	9.782E-003	1	9.782E-003	1.41	0.2504	0.22
Pure error	0.014	4	3.380E-003			0.32
Total	4.3358					

various parameters on the responses using ANOVA at a significant level of 0.05 (Mohanty, 2015; Vishnu Vardhan et al., 2017).

Equations (4-6) obtained from regression analysis in terms of actual factors are given below:

$$\begin{aligned} \text{MRR} = {} & +96981.69 + 1543.36 \text{ x } A - 1.84 \text{ x } 10^5 \text{x } B - 62426.32 \text{x} C \\ & - 1.5 \text{ x } 10^5 \text{x} D + 1335.71 \text{x} AC + 1558.33 \text{ x } AD + 1.67 \text{ x} 10^5 \text{x } BD \\ & + 9116.74 \text{ x } CD - 27.22 \text{ x } A^2 - 22762.87 \text{ x } C^2 \end{aligned} \tag{4}$$

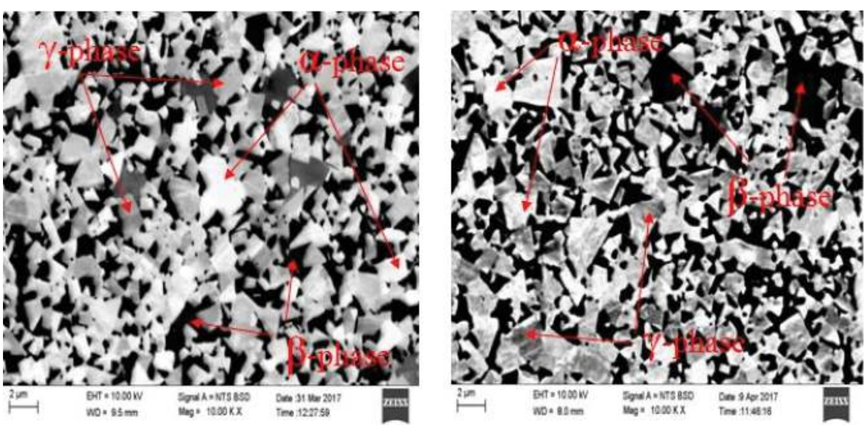
$$\begin{aligned} \text{TWR} = {} & +66.96 + 0.56 \text{ x } A - 119.81 \text{ x } B - 1.3 \text{x} C - 57.58 \text{ x } D \\ & + 0.42 \text{ x } AC + 0.45 \text{ x } AD - 168.78 \text{ x } BC - 2.11 \text{ x } CD \\ & - 6.7 \text{x } 10^{-3} \text{x } A^2 + 1113.77 \text{ x } B^2 + 4.69 \text{ x } C^2 + 1.46 \text{ x } D^2 \end{aligned} \tag{5}$$

$$\begin{aligned} \text{Surface Roughness} = {} & -1.176 + 0.049 \text{ x } A + 4.83 \text{ x } B + 1.25 \text{ x } C + 0.43 \text{ x } D \\ & - 2.95 \text{ x } BD - 0.36 \text{ x } CD - 4.1 \text{x} 10^{-4} \text{x } A^2 + 9.97 \text{ x } B^2 \\ & - 0.16 \text{ x } C^2 - 0.04 \text{ x } D^2 \end{aligned} \tag{6}$$

5.1. Microstructural analysis

The microstructural analysis on tungsten carbide cutting tools was conducted using ZEISS SEM at DRDL, Hyderabad. The metallographic determination of microstructure was made in accordance with ASTM B390-92 (standard practice for evaluating apparent grain size and distribution of cemented tungsten carbides) and ASTM B657-92 (metallographic determination of microstructure in cemented carbides). The following phases are present in the metallographic microstructure of ASM Metal Hand Book (Sanathanam, 2004). (a) Alpha (α-phase) tungsten carbide (WC), (b) beta (β-phase)cobalt binder (c) gamma (η-phase) carbides of the cubic lattice (TaC, TiC, etc.) and (d) eta (η-phase) multiple carbides tungsten and at least one metal binder. In the present study, the selected grade of carbide contains small amounts of other carbides (other than tungsten carbide) and the η phase is insignificant. The microstructure of DCT and untreated tungsten carbide cutting tool is shown in Figure 6(a,b). It is evident from the microstructure that only α, β and η phases are identified, but γ phase is not present since a very few presence of TiC and TaC. A similar type of analysis has been found elsewhere (Gill et al., 2011; Vishnu Vardhan et al., 2018). The steady shape of rigid α-phase grains is a triangular prism which is not completely developed due to deposition of different grains. As shown in Figure 6, the normal size of α-phase grains in the microstructure of the DCT tungsten carbide tools is larger than the untreated tools. The raise in the α-phase grain size of DCT tungsten carbide material enhances the thermal conductivity (Gill et al., 2011; Thamizhmanii & Mohd Nagib, 2011). In cryo-treatment process, the hard α-phase grains are developed into their highly stable state. It makes the hard α-phase grain structure into durable and stress free formation which results in a reduction in stress induced fractures and thus enhances the cutting tool life.

Surface morphology of the P20 work material was analyzed at RUSKA Labs, Hyderabad. Figure 7(a,b) shows SEM micrographs of machined surface at A = 75 m/min, B = 0.15 mm/tooth, C = 1 mm, D = DCT 36 h and A = 75 m/min, B = 0.1 mm/tooth, C = 1 mm, D = DCT 0 h (untreated tool) respectively from experiment numbers 8 and 21. It is observed from the SEM micrographs that surface quality is improved on the machined surface with DCT 36-h treated tool compared with the untreated tool.



(a) (b)

Figure 6. Microstructure of tungsten carbide tools (a) DCT; (b) untreated tool.

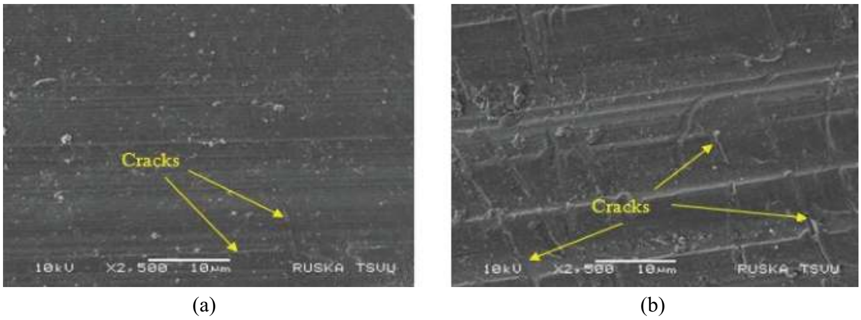


Figure 7. SEM micrograph of machined surface at (a) A = 75 mm/min, B = 0.15 mm/tooth, C = 1 mm, D = DCT 36 h (b) A = 75 mm/min, B = 0.15 mm/tooth, C = 1 mm, D = DCT 0 h.

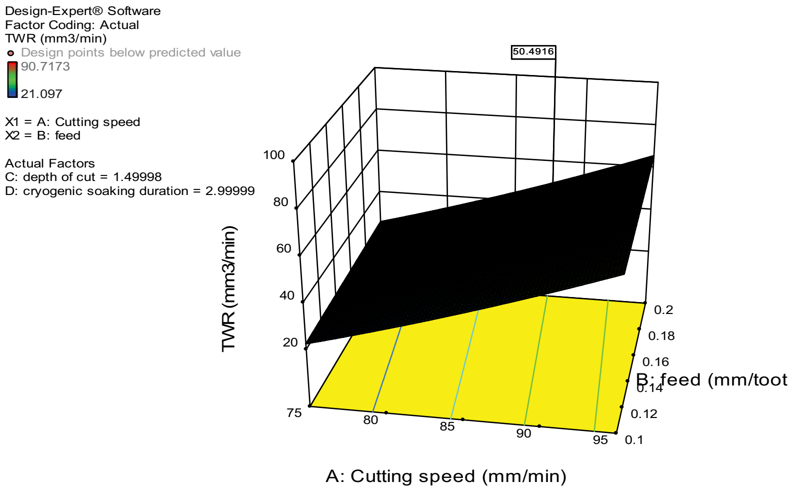
5.2. Surface plots

Figure 8(a) shows the surface plots for variation of TWR with cutting speed and feed. From the figure, it is clear that TWR increases with increase in cutting speed. The increase in cutting speed directly affects the cutting. TWR was seemed to be higher at higher cutting speeds (Khan & Maity, 2017). The increase in cutting speed raises the temperature in the machining zone. This causes the higher temperature at the tip of the cutting edges of the tool; therefore, the strength of the tool reduces and as soon as the tool contacts the work surface at this situation, TWR becomes more (Kondayya & Gopala Krishna, 2012; Yong et al., 2007).

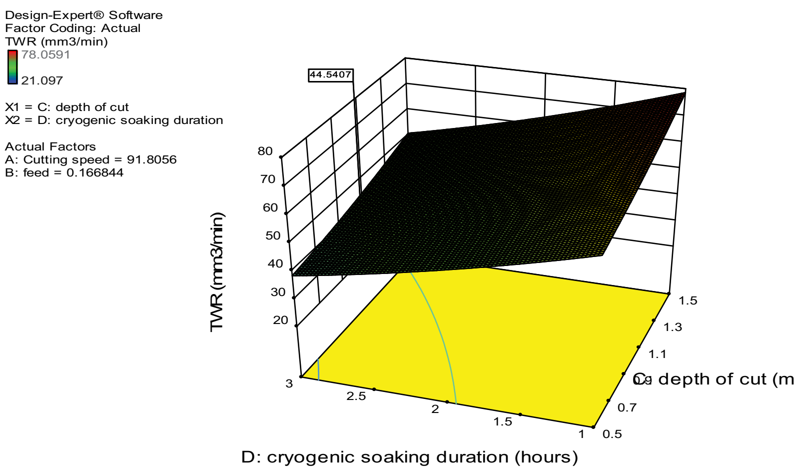
Figure 8(b) shows the surface plot for variation TWR with cryogenic soaking duration and depth of cut. The advantage offered due to deep cryogenically treated tool over untreated tool is shown in Figure 8(b). It is clear from the graph that cryogenically treated tool wear is less than the untreated tool which clearly shows that cryogenic soaking duration of the tool is a most influential parameter for reducing the TWR. This major decrease in TWR of DCT tools over untreated tools might be owing to the fact that at lower cutting speeds, result in wear resistance properties produced in the cryogenic treatment of tools. Cryo-treatment also contributes considerably in cooling the tip of the tool by enhancing the thermal conductivity of the tool material which easily dissipates heat to the surroundings (Giasin et al., 2016; Sartori et al., 2016; Wang et al., 2017; Yong et al., 2007).

Figure 8(c) shows the effect of DCT of tools on MRR. From Figure 8(c), it can be obviously seen that MRR is gradually increasing while machining with a DCT cutting tool than an untreated cutting tool. This is due to the fact that tool wear is gradually reduced by deep cryo-treatment, so proper geometry of the tool is retained. So with proper retention of sharp edges of cutting tool better chip formability is obtained and thus MRR is increasing (Singh et al., 2011).

Figure 8(d) shows the effect of DCT of the tool on R_a. From Figure 8(d), it can be clearly seen that with an increase in cutting speed, the R_a is reducing and with an increase in soaking duration, the R_a is decreasing. This shows that DCT soaking duration and cutting speed are more influencing the R_a. Enhancement in thermal conductivity of cutting tools due to DCT results in less tool wear makes the machined surface smooth (Sartori et al., 2016; Wang et al., 2017; Yong et al., 2007).



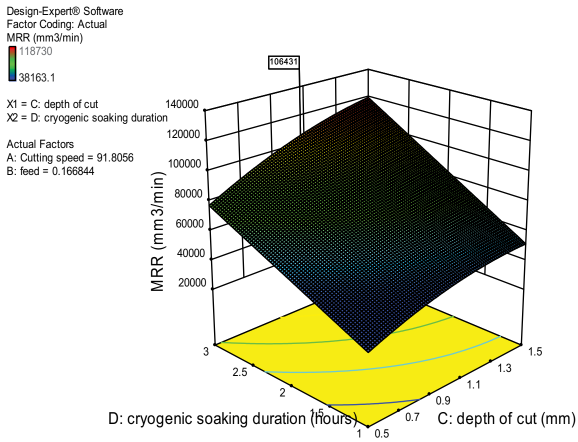
(a)



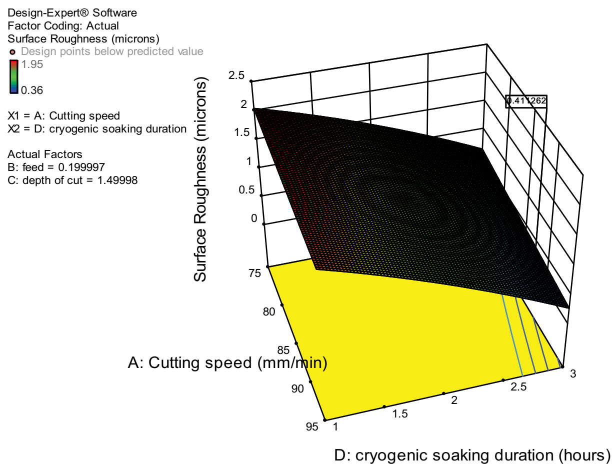
(b)

Figure 8. Surface plots of (a) TWR with cutting speed and feed, (b) TWR with cryogenic soaking duration and depth of cut, (c) MRR with deep cryogenic soaking duration and depth of cut, (d) R_a with cryogenic soaking duration and cutting speed, (e) MRR with cutting speed and feed, (f) R_a with feed and depth of cut.

Figure 8(e) shows the surface plot of MRR with cutting speed and feed. It is clearly observed that MRR is increasing with increase in cutting speed and feed. It is due to the fact that the cutting temperature is higher at higher cutting speeds, resulting in softening the effect of the work piece at higher cutting speeds. Figure 8(f) shows the surface plot of R_a with feed and depth of cut. It is observed that R_a increasing with increase in the feed as well as the depth of cut. It is known that the feed rate is the most influential parameter negatively affecting R_a. For this reason, in order to improve the surface quality, the feed rate should be reduced as much as possible.



(c)



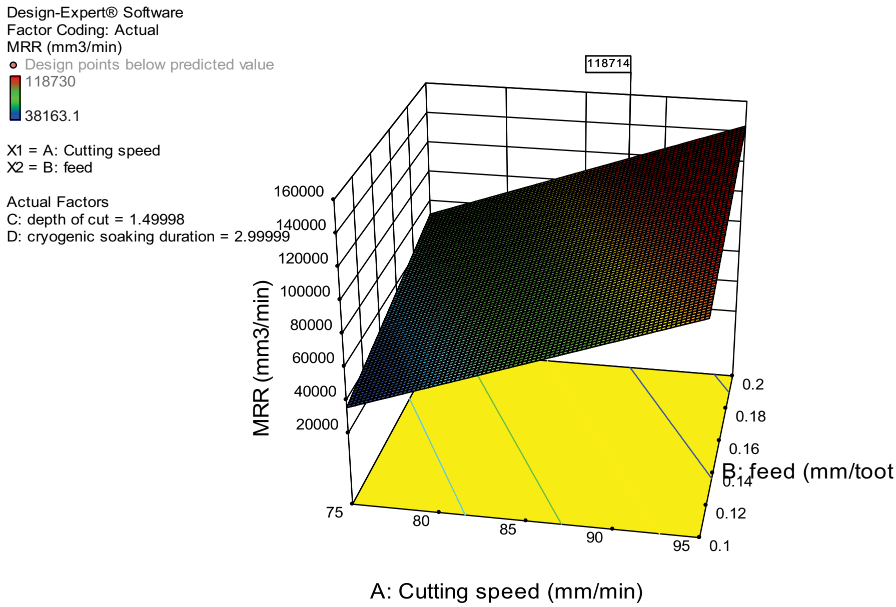
(d)

Figure 8. Countinued.

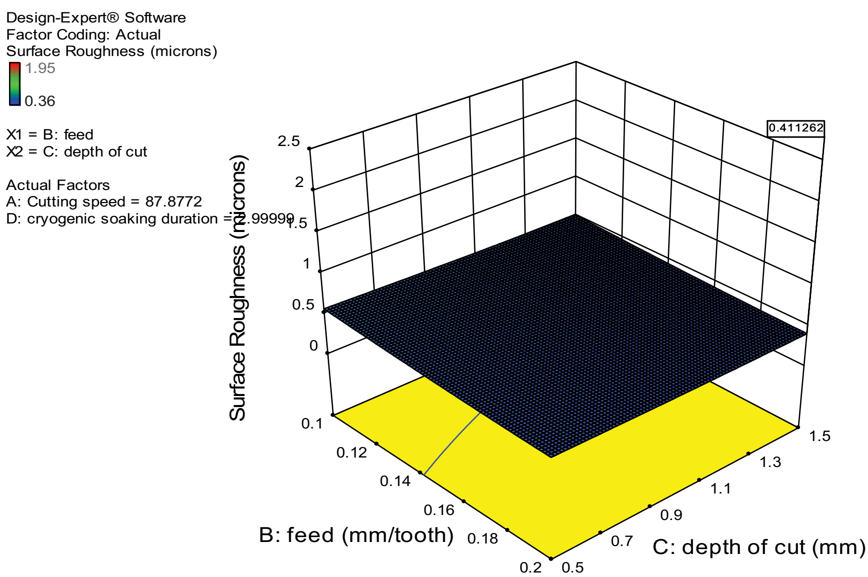
As discussed earlier in this article, cryogenic treatment can significantly decrease the TWR which increases the tool life of the cutting tool; R_a also improves by the DCT tool. Therefore, it can be expected that cutting tools which are subjected to DCT efficiently reduce the TWR while machining at high cutting speeds which comparatively affects R_a and MRR of the machined work part.

5.2.1. Formulation of multi objective optimization problem and optimization

In this article, three responses such as MRR, TWR and R_a are considered. At a time two different responses are considered to optimize taking other response as a constraint. The constrained value is taken from the experiment. The final relations between input parameters and output responses in terms of actual factors formed from the RSM method is utilized as an objective function to solve the optimization problem.



(e)



(f)

Figure 8. Countinued.

In this study, the goals are the maximization of MRR and minimization of TWR and R_a. Three optimization problems are framed taking two different responses as objectives and one as a constraint. The relations obtained in Equations (4–6) between input parameters and output responses are utilized as functional relations. NSGA-II algorithm is used in MATLAB to solve optimization problems:

(1) Maximize MRR
Minimize TWR

Subject to $R_a \leq 0.36$

Where 0.36 is the lowest value of R_a obtained from the experiment table

(2) Maximize MRR
Minimize R_a

Subject to TWR ≤ 21.097

Where 21.097 is the lowest value of TWR obtained from the experiment table

(3) Minimize TWR
Minimize R_a

Subject to MRR ≥ 118,730

Where 118,730 is the maximum value of MRR obtained from the experiment table

It is to be noted that wherever an objective function has to be maximized, consequent minimization function is utilized in the MATLAB program (Mohanty, 2015; Mohanty et al., 2014).

Based on the exhaustive experimentation Figure 9(a-c) is drawn to judge the Pareto front among objectives MRR-TWR, MRR-R_a and TWR-R_a, respectively.

At this point, a primary population size of 70 is considered and optimization is performed. Based on NSGA-II algorithm, rankings and sorting of solutions are done and the final Pareto-optimal solution set is shown in Table 6. It must be eminent that all the solutions are simultaneously excellent and any solution set of process parameters can be taken to attain the equivalent response values depending upon machining conditions (Mohanty, 2015; Vishnu Vardhan et al., 2018). Validation experiments were carried out by running a combination of process parameters in the CNC end milling of P20 steel and obtained 95% confidence level.

6. Conclusions

This article aimed to study the effect of DCT on tungsten carbide cutting tools subjected to various soaking duration while machining P20 steel work piece in the CNC end milling process. SEM analysis is performed to know the possible microstructural changes occurred during DCT for the treated and untreated tools. Finally, an integrated method of RSM combined with the NSGA-II for optimization of the process parameters in CNC milling on machinability of P20 steel is proposed. In this way, a new evolutionary approach for optimization has been proposed and the Pareto optimal solutions are obtained. The Pareto optimal set of solutions obtained can be utilized to select the best machining condition for CNC milling process to increase the productivity of the process.

Based on the experimentation and analysis of the results, the conclusions can be made as follows:

(1) The DCT soaking duration can significantly improve the life of the end mill carbide cutting tools. However long cryogenic soaking duration is mostly influencing the tool wear compared to other soaking duration.
(2) MRR is high during machining with 36-h DCT soaking duration cutting tool compared with other cutting tools followed by 24-h DCT soaking duration cutting tool.

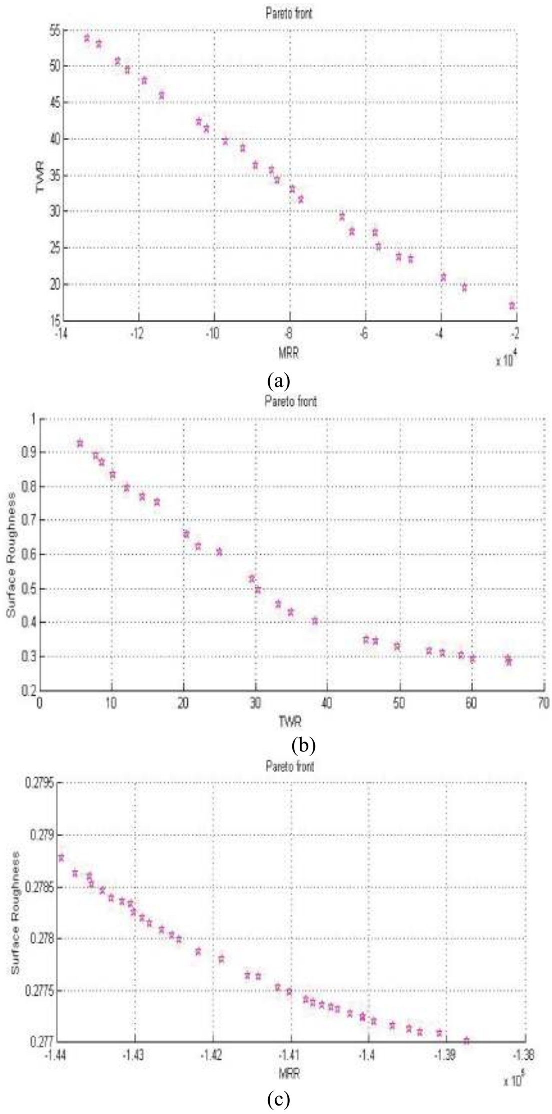


Figure 9. Pareto front for objectives (a) MRR vs. TWR (b) TWR vs. R_a (c) MRR vs. $R_{a.}$

Untreated cutting tool exhibits the poorest performance with regard to MRR, TWR and R_a.

(3) Through SEM analysis on cutting tools, it was observed that DCT reduced the TWR by increasing the thermal conductivity. From SEM analysis of the machined surface of the work piece, it is observed that surface quality has improved on the machined surface with DCT tool compared with the untreated tool.

(4) From the analysis, it can be concluded that 36-h-soaked tools (Cryogenic treatment) are more suitable to machine the P20 steel than the DCT cutting tool for 24-h soaking duration and untreated cutting tools.

Table 6. Pareto optimum solutions for MRR vs. TWR.

S. No.	MRR	TWR	Cutting speed	Feed	Depth of cut	Cryogenic soaking duration
1	−118,625.72	53.80	92.85	0.20	1.50	3.00
2	−21,134.11	16.95	75.04	0.11	0.55	2.99
3	−96,920.24	39.63	83.29	0.19	1.37	2.98
4	−39,351.23	20.85	75.69	0.14	0.70	2.99
5	−56,473.90	25.15	75.50	0.17	0.97	2.98
6	−79,313.74	33.02	78.75	0.20	1.15	2.98
7	−83,377.53	34.25	80.14	0.20	1.14	2.99
8	−66,204.81	29.20	76.37	0.18	1.44	3.00
9	−84,836.17	35.73	81.54	0.20	1.01	2.99
10	−33,736.00	19.49	75.39	0.13	0.67	2.99
11	−63,598.56	27.25	76.54	0.18	1.06	2.99
12	−51,223.37	23.70	75.14	0.17	0.88	2.98
13	−48,046.87	23.39	75.49	0.14	1.03	2.99
14	−21,134.11	16.95	75.04	0.11	0.55	2.99
15	−118,524.13	49.44	91.18	0.20	1.31	3.00
16	−57,527.47	27.12	79.80	0.15	0.75	2.99
17	−102,034.47	41.37	85.27	0.20	1.19	2.99
18	−116,520.25	50.70	92.38	0.19	1.34	3.00
19	−104,117.91	42.26	85.68	0.19	1.30	2.99
20	−89,052.70	36.28	81.74	0.19	1.20	2.99
21	−113,842.95	45.91	87.20	0.20	1.45	2.99
22	−110,477.31	52.97	92.59	0.20	1.47	2.99
23	−77,074.31	31.64	78.34	0.19	1.23	3.00
24	−92,346.78	38.65	85.43	0.17	1.15	2.99
25	−118,518.15	47.98	90.35	0.20	1.25	2.99

(5) However, study on effect of cooling and warming periods was not in the domain of study of present work however this can be added for future work.
(6) Process parameters with different coatings on cutting tool materials, wet and dry machining, cooling temperature and tempering cycle need to analyze and optimize the CNC milling process.

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References

Arockia Jaswin, M., & Mohan Lal, D. (2010). Optimization of the cryogenic treatment process for En 52 valve steel using the Grey-Taguchi method. *Materials and Manufacturing Processes*, *25*(8), 842–850. https://doi.org/10.1080/10426910903536766

Arokiadass, R. (2015). Parametric optimization of end milling of Al/SiCp composites using NSGA-II. *International Journal of Advanced Materials Research*, *1*(3), 86–94. https://pdfs.semanticscholar.org/b9ee/054baa6f556fc900df39dd0806d6200d1c1f.pdf

Routara, B.C., Bandyopadhyay, A., & Sahoo, P. (2009). Roughness modeling and optimization in CNC end milling using response surface method: Effect of workpiece material variation. *The International Journal, Advanced Manufacturing Technology*, *40*(11), 1166–1180. https://doi.org/10.1007/s00170-008-1440-6

Cajner, F., Leskovsek, V., Landek, D. & Hrvoje Cajner. (2008). The effect of deep-cryogenic treatment on high-speed steel properties. *Materials and Manufacturing Processes*, *24*(7–8), 743–746. https://doi.org/10.1080/10426910902809743

Chen-hui, X. I. E., Ji-wu, H. U. A. N. G., Yun-feng, T. A. N. G., & Li-ning, G. U. (2015). Effects of deep cryogenic treatment on microstructure and properties of WC–11Co cemented carbides with various carbon contents. *Transactions of Nonferrous Metals Society of China*, *25(9)*, 3023–3028. https://doi.org/10.1016/S1003-6326(15)63929-2

Chetan, S. Ghosh, & Rao, P. V. (2017). Performance evaluation of deep cryogenic processed carbide inserts during dry turning of Nimonic 90 aerospace grade alloy. *Tribology International*, *115*, 397–408. https://doi.org/10.1016/j.triboint.2017.06.013

Cicek, A., Kara, F., & TurgayKivak. (2013). Evaluation of machinability of hardened and cryo-treated AISI H13 hot work tool steel with ceramic inserts. *International Journal of Refractory Metals and Hard Materials*, *41*(1), 461–469. https://doi.org/10.1016/j.ijrmhm.2013.06.004

Nadig, D.S., Jacob, S., Karunanithi, R., Manjunatha, R., Subramanian, D., Prasad, M. V. N., Sen, G., & Jha, A. K. (2010). Studies of cryo treatment on the performance of integral diaphragm pressure transducers for space application. *Cryogenics*, *50*(9), 561–565. https://doi.org/10.1016/j.cryogenics.2010.02.016

Datta, R., & Kalyanmoy Deb, A. (2009). Classical-cum-evolutionary multi-objective optimization for optimal machining parameters. *World Congress on Nature and Biologically Inspired Computing*, 607–612. https://doi.org/10.1109/NABIC.2009.5393425

Deb, K. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, *6*(2), 187–192. https://doi.org/10.1109/4235.996017

Dhar, R., Nanda Kishore, S. V., & Paul, S. (2002). The effects of cryogenic cooling on chips and cutting forces in turning AISI 1040 and AISI 4320 steels. Proc IMechE Part B. *Journal of Engineering Manufacture*, *216*(5), 713–724. https://doi.org/10.1243/0954405021520409

Dieringa, H. (2017). Influence of cryogenic temperatures on the microstructure and mechanical properties of magnesium alloys: A review. *Metals*, *7*(2), 38. https://doi.org/10.3390/met7020038

Giasin, K., Ayvar-Soberanis, S., & Hodzic, A. (2016). Evaluation of cryogenic cooling and minimum quantity lubrication effects on machining GLARE laminates using the design of experiments. *Journal of Cleaner Production*, *135*, 533–548. https://doi.org/10.1016/j.jclepro.2016.06.098

Gill, S. S., Singh, H., & Singh, R. (2011). Flank wear and machining performance of cryogenically treated tungsten carbide inserts. *Materials and Manufacturing Processes*, *26*(11), 1430–1441. https://doi.org/10.1080/10426914.2011.557128

Pang, J.S., M N M, A., & Zaroog, O. S. (2014). Taguchi design optimization of machining parameters on the CNC end milling process of halloysite nano tube with aluminum reinforced epoxy matrix (HNT/Al/Ep) hybrid composite. *HBRC Journal*, *10*(2), 138–144. https://doi.org/10.1016/j.hbrcj.2013.09.007

Jie, L., Zhao, J., & Liu, Q. (2013). Optimization of cutting parameters based on multi-objective genetic algorithm NSGA-II. *Applied Mechanics and Materials*, *281*, 517–522. https://doi.org/10.4028/www.scientific.net/AMM.281.517

Jun, L., Yang, X., & Ren, C. (2014). Multi-objective optimization of cutting parameters in Ti-6Al-4V milling process using non-dominated sorting genetic algorithm-II. *The International Journalof Advanced Manufacturing Technology*, *76*(5), 941–953.https://doi.org/10.1007/s00170-014-6311-8

Junji, L., Yan, X., Liang, X., Hong, G., & Li, D. Y. (2016). Influence of different cryogenic treatments on high-temperature wear behavior of M2 steel. *Wear*, *377*(Part B), 1112–1121. https://doi.org/10.1016/j.wear.2016.11.041

Kalyan Kumar, K. V. B. S., & Choudhury, S. K. (2008). Investigation of tool wear and cutting force in cryogenic machining using the design of experiments. *Journal of Materials Processing Technology*, *203*(1–3), 95–101. https://doi.org/10.1016/j.jmatprotec.2007.10.036

Khan, A. A., & Mirghani Ahmed, I. (2008). Improving tool life using cryogenic cooling. *Journal of Materials Processing Technology*, *196*(1–3), 149–154. https://doi.org/10.1016/j.jmatprotec.2007.05.030

Khan, A., & Maity, K. (2017). Parametric modelling of multiple quality characteristics in turning of CP titanium grade-2 with cryo-treated inserts. *International Journal of Materials and Product Technology*, *54*(4), 306–331. https://doi.org/10.1504/IJMPT.2017.082622

Kondayya, D., & Gopala Krishna, A. (2012). An integrated evolutionary approach for modeling and optimization of CNC end milling process. *Computer Integrated Manufacturing*, *25*(11), 1069–1084. https://doi.org/10.1080/0951192X.2012.684718

Maiyar, L. M., Ramanujam, R., Venkatesan, K.& Jerald J. (2013). Optimization of machining parameters for end milling of inconel 718 super alloy using Taguchi based Grey relational analysis. *Procedia Engineering*, *64*, 1276–1282. https://doi.org/10.1016/j.proeng.2013.09.208

Mohanty, C. P., Mahapatra, S. S., & Singh, M. R. (2014). A particle swarm approach for multi-objective optimization of electrical discharge machining process. *Journal of Intelligent Manufacturing*, *27*(6), 1–20. https://doi.org/10.1007/s10845-014-0942-3

Mohanty, C. P. (2015). *Studies on some aspects of multi-objective optimization: A case study of electrical discharge machining process* [E-Thesis]. NIT.

Nalbant, M., & Yildiz, Y. (2011). Effect of cryogenic cooling in milling process of AISI 304 stainless steel. *Transactions of Non-ferrous Metals Society of China*, *21*(1), 72–79. https://doi.org/10.1016/S1003-6326(11)60680-8

Nirmal Kalsi, S., Sehgal, R., & Vishal Sharma, S. (2010). Cryogenic treatment of tool materials: A review. *Materials and Manufacturing Processes*, *25*(10), 1077–1100. https://doi.org/10.1080/10426911003720862

Oktem, H., Erzurumlu, T., & Kurtaran, H. (2005). Application of response surface methodology in the optimization of cutting conditions for surface roughness. *Journal of Materials Processing Technology*, *170*(1-2), 11–16. https://doi.org/10.1016/j.jmatprotec.2005.04.096

Ozbek, N. A., Cicek, A., & Gulesin, M. (2014). Investigation of the effects of cryogenic treatment applied at different holding times to cemented carbide inserts on tool wear. *International Journal of Machine Tools and Manufacture*, *86*, 34–43. https://doi.org/10.1016/j.ijmachtools.2014.06.007

Padhee, S., Nayak, N., Panda, S. K., Dhal, P. R., & Mahapatra, S. S. (2012). Multi-objective parametric optimization of powder mixed electro-discharge machining using response surface methodology and NSGA-II. *Sadhana*, *37*(2), 223–240. https://doi.org/10.1007/s12046-012-0078-0

Podgornik, B., Paulin, I., Zajec, B., Jacobson, S., & Leskovsek, V. (2016). Deep cryogenic treatment of tool steels. *Journal of Materials Processing Technology*, *229*, 398–406. https://doi.org/10.1016/j.jmatprotec.2015.09.045

Sahoo, A. K., & Sahoo, B. (2013). Performance studies of multilayer hard surface coatings (TiN/TiCN/Al_2O_3/TiN) of indexable carbide inserts in hard machining: Part-II (RSM, gray relational and techno-economical approach). *Measurement*, *46*(8), 2868–2884. https://doi.org/10.1016/j.measurement.2012.09.023

Sanathanam, A. T. (2004). Kennametal Inc., Cemented carbides, ASM metal hand book. *Metallography of Cemented Carbides*, *9*, 1066–1077. https://doi.org/10.31399/asm.hb.v09.a0003797

Sartori, S., Moro, L., Ghiotti, A., & Bruschi, S. (2016). On the tool wear mechanisms in dry and cryogenic turning additive manufactured titanium alloys. *Tribology International*, *105*, 264–273. https://doi.org/10.1016/j.triboint.2016.09.034

Seah, K. H. W., Rahman, M., & Yong, K. H. (2003). Performance evaluation of cryogenically treated tungsten carbide cutting tool inserts.Proc IMechE Part B. *Journal of Engineering Manufacture*, *217*(1), 29–43. https://doi.org/10.1243/095440503762502260

Sheng, Q., Zhao, J., & Wang, T. (2016). Experimental study and machining parameter optimization in milling thin-walled plates based on NSGA-II. *International Journal of Advanced Manufacturing Technology*, *89*(5), 2399–2409. https://doi.org/10.1007/s00170-016-9265-1

Shokrani, A., Dhokia, V., & Stephen Newman, T. (2016). Investigation of the effects of cryogenic machining on surface integrity in CNC end milling of Ti–6Al–4V titanium alloy. *Journal of Manufacturing Processes*, *21*, 172–179. https://doi.org/10.1016/j.jmapro.2015.12.002

Singh, S., Singh, S., & Singh, J. (2011). Improvement in tool life of M2HSS tools by cryogenic treatment. *Journal of Metallurgical Engineering*, *1*(1–2), 47–61.

Sobotova, J., Jurci, P., & Dlouhy, I. (2016). The effect of sub zero treatment on microstructure, fracture toughness, and wear resistance of Vanadis 6 tool steel. *Materials Science and Engineering A*, *652*, 192–204. https://doi.org/10.1016/j.msea.2015.11.078

Sreenivasulu, R. (2013). Optimization of surface roughness and delamination damage of GFRP composite material in end milling using Taguchi design method and artificial neural network. *Procedia Engineering*, *64*, 785–794. https://doi.org/10.1016/j.proeng.2013.09.154

Swamini, A., Chopra, & Sargade, V. G. (2015). Metallurgy behind the cryogenic treatment of cutting tools: An overview. *Materials Today: Proceedings*, *2*(4-5), 1814–1824. https://doi.org/10.1016/j.matpr.2015.07.119

Reddy, T.V.S., Sorna Kumar, T., & Venkatarama Reddy, M. (2009). Turning studies of deep cryogenic treated p-40 tungsten carbide cutting tool inserts – Technical communication. *Machining Science and Technology*, *13*(2), 269–281. https://doi.org/10.1080/10910340902979754

Thamizhmanii, S., & Mohd Nagib, S. H. (2011). Performance of deep cryogenically treated and non-treated PVD inserts in milling. *Journal of Achievements in Materials and Manufacturing Engineering*, *49*(2), 460–466. http://jamme.acmsse.h2.pl/papers_vol49_2/49237.pdf

Vadivel, K., & Rudramoorthy, R. (2009). Performance analysis of cryogenically treated coated carbide inserts. *International Journal of Advanced Manufacturing Technology*, *42*(3), 222–232. https://doi.org/10.1007/s00170-008-1597-z

Vishnu Vardhan, M., Sankaraiah, G., & Yohan, M. (2018). Effect of cryogenic treatment of tungsten carbide tools on cutting force and power consumption in CNC milling process. *Production and Manufacturing Research*, *6*(1), 149–170. https://doi.org/10.1080/21693277.2018.1436011

Vishnu Vardhan, M., Sankaraiah, G., Dr., Yohan, M., Dr., & Jeevan Rao, H. (2017). Optimization of parameters in CNC milling of p20 steel using response surface methodology and Taguchi method. *Materials Today: Proceedings*, *4*(8), 9163–9169. https://doi.org/10.1016/j.matpr.2017.07.273

Wang, F., Liu, J., & Shu, Q. (2017). Optimization of cryogenic milling parameters for AFRP. *The International Journal of Advanced Manufacturing Technology*, *91*(9–12), 3243–3252. https://doi.org/10.1007/s00170-017-0003-0

Yang, G., Bing-Hui, L., Zhen-hai, B., Bin, Z., & Sheng, O. (2016). Effects of deep cryogenic treatment on the microstructure and properties of WC-Fe-Ni cemented carbides. *International Journal of Refractory Metals and HardMaterials*, *58*, 42–50. https://doi.org/10.1016/j.ijrmhm.2016.03.010

Yong, A. Y. L., Seah, K. H. W., & Rahman, M. (2007). Performance of cryogenically treated tungsten carbide tools in milling operations. *The International Journal of Advanced Manufacturing Technology*, *32*(7), 638–643. https://doi.org/10.1007/s00170-005-0379-0

Zhang, C., Weidong, L., & Jiang, P. (2016). Experimental investigation and multi-objective optimization approach for low-carbon milling operation of aluminum. *Proc IMechE Part C: Journal of Mechanical Engineering Science*, *231*(15), 2753–2772. https://doi.org/10.1177/0954406216640574

Zhang, J. Z., Chen, J. C., & Daniel Kirby, E. (2007). Surface roughness optimization in an end-milling operation using the Taguchi design method. *Journal of Materials Processing Technology*, *184*(1–3), 233–239. https://doi.org/10.1016/j.jmatprotec.2006.11.029