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A comparative study on performance of CBN inserts when turning steel under dry and wet conditions

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Abstract. Cutting fluids is the most unsustainable components of machining processes, it is negatively impacting on the environmental and additional energy required. Due to its high strength and corrosion resistance, the machinability of stainless steel has attracted considerable interest. This study aims to evaluate performance of cubic boron nitride (CBN) inserts for the machining parameters includes the power consumption and surface roughness. Due to the high single cutting-edge cost of CBN, the performance of significant is importance for hard finish turning. The present work also deals with a comparative study on power consumption and surface roughness under dry and flood conditions. Turning process of the stainless steel 316 was performed. A response surface methodology based box-behnken design (BBD) was utilized for statistical analysis. The optimum process parameters are determined as the overall performance index. The comparison study has been done between dry and wet stainless-steel cut in terms of minimum value of energy and surface roughness. The result shows the stainless still can be machined under dry condition with 18.57% improvement of power consumption and acceptable quality compare to the wet cutting. The CBN tools under dry cutting stainless steel can be used to reduce the environment impacts in terms of no cutting fluid use and less energy required which is effected in machining productivity and profit.

1. Introduction

Hard finish turning is an excellent process compare to traditional grinding as a finishing process. Beside the productivity, machining process must to be attention about sustainable of product by developing a new approach with the lowest environmental impact possible. Sustainable manufacturing means concerns about energy, health safety, cost and environmental aspects. The energy is playing very big role on manufacturing sustainability. It has a negative impact on the environment. Improvement of energy efficiency one of the most the world's interests [1]. In 2010, the consumption of energy globally was 524 quadrillion Btu, and is expected to increase to 630 quadrillion Btu in the next five years [2]. Direct emission of greenhouse gases such as carbon dioxide (CO_2) generates by use of fossil fuels and released into the environment during power generation. The average emission factor for electricity was 0.5488 kg per kWh in China in 2009 [3], it is indicated that 0.5488 kg CO_2 was released when generated 1 kWh. In USA, the total CO_2 emission was 5802 million metric tons in 2008, and the industry sector was contributed by 27.4% [4]. Moreover, from economic side, the rapid increase in the price of fossil fuels and electricity. Therefore, the unit production cost will be increase. Saving energy is the concerns for most of the industrial processes. Usually, the energy consumption is not considering as machine responses and very limited research has been performed includes energy consumption [5]. Cutting fluid one of the most factors influence of environmental and workers. A common practice in machining process is mostly using cutting fluids. Although overall machinability can be improved by reducing temperature and friction at the cutting region [6], but lubrication fluids based oil considering unsustainable factor of cutting processes [7]. Addationaly, the energy consumption, maintenance and service for coolant system, and waste/disposal of cutting fluids [8], which means growing environmental issues, as well as higher manufacturing cost [9,10]. Therefore, cutting process effect should be minimized when that possible by performing dry cutting strategies [11,12] to decrease coolant impacts and costs.

Besides power consumption and cutting fluid, Cutting tool considered as one of the most factors effects in machine performance in terms of surface quality, production rate and product cost [13]. The cutting tools cost is ~4% of the total manufacturing cost [14]. For hard turning superior steel, cubic boron nitride (CBN) inserts are usually used to achieve very high accuracy and surface texture [15]. CBN tools are advanced cutting tools when machining heat resistant alloys [16], with impact resistance and good wear. its stable hot hardness, strength, toughness, wear resistance and also chemical stability at high temperatures around 1000ºC for the superior hardened steel parts [17–19]. Due to the high single cutting edge cost of CBN, the performance of significant is importance for hard finish turning. Many research [20–28] has been done in hard material machining to investigate the machine performance of variation type of cutting tool under different conditions. The stainless steel is extensively used in many applications such as aerospace, automotive, a component of contracture, chemical production, power plants, and medical instruments. Stainless steel considers as difficult to machine due to a high tool wear, work hardening, poor surface quality, low productivity, and high machining costs [29]. Machinability study and sustainable on the stainless steel still is of interest [5].

Due to importance of cutting parameters on the machining performance, the analyze impact of machining parameters helped toward reducing the power consumption and enhancement of sustaniable [30–33]. Therefore, The appropriate selection of machining parameters plays a significant role in ensuring the quality of product [31], increasing the tool life [34], reducing power consumption [35], and increasing production rate [36]. Consequently, this study proposes to evaluate the contribution of cutting parameters during machining turning of AISI 316 steel on the power consumption, surface roughness under dry and wet condition. In this research, three main cutting parameters (cutting speed, depth of cut, and feed rate) were optimized to minimize energy consumption, and surface roughness during the turning of AISI316 under dry and wet conditions using response surface methodology based box-behnken design (BBD). The comparison study has been done between dry and wet stainless steel cut in terms of minimum value of energy and surface roughness.

2. Experimental details

2.1. Work Piece Materials and Cutting inserts

The workpiece material used for this investigation is a cylindrical rod of stainless steel 316 with axial length of 80 mm and diameter of 60 mm. The composition of the stainless steel 316 tabulated in Table 1.

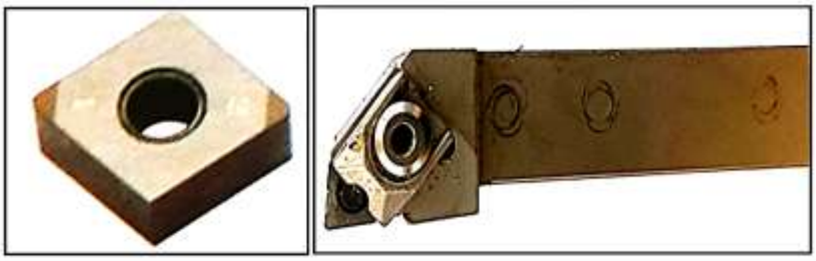
Table 1. Chemical composition of the AISI316.

Material	C	Si	Mn	Ni	S	Cr	Mo
Wt. %	0.078	0.337	5.81	3.68	0.29	18.28	0.049

Table 2. Cutting conditions.

Workpiece	**Cutting speed**	**Feeds**	**Depth of cut**	**Cutting condition**
AISI316 steel	(110 -140 -170) m/min	(0.1- 0.15-0.2) mm/rev	(0.8 -1.25-1.4) mm	Dry, Wet
Cutting tools	**Young's modulus**	**Tool geometry**	**Tool holder**	**Responses**
CBN, 92.4 +1 HRA	47 (10^3kgf/mm^2)	CNMG 120408, 80° diamond sharp and 0° relief angle	BCLNR2525M12	power consumed and surface roughness

The cutting tool used for this study, CBN cutting tool, the tool was designated as ISO CNMG 120408, with 80° diamond sharp and 0° relief angle (Fig.1). The details about tool holder and other cutting condition tabled in Table 2. The turning process was performed in both condition with and without cutting fluid used.



(a) (b)

Figure 1. (a) CBN inserts tools (b) Tool holder.

2.2. Method

The experiments were conducted according to the box-behnken design matrix and responses as shown in Table 3. A fresh insert was used for each experiment in order to improve the reliability of results. In present experiment, there are three (3) influences cutting parameters which are cutting speed (v_c) with the rang of (110 -140 -170 m/min), feed rate (*fr*) with the rang of (0.1- 0.15-0.2 mm/rev), and depth of cut (a_p) with the rang of (0.8 -1.25-1.4 mm) with their five (3) levels. The range each factor was selected is adapted from the Karoly handbook [37] and based on preliminary trials. Previous studies have used similar factor ranges to investigate similar responses [5,38,39]. In the present investigation, a response surface methodology (RSM) based box-behnken design was selected. A series of 15 experiments includes three center points were formulated to carry out experimental work (Table 3). The responses determined during the experiments were the power consumed during cutting stage (PW) in Wh, and average surface roughness (R_a) in µm. The turning experiments were performed using CNC lathe ROM 240 with (100 to 4000 rpm) a spindle speed range. Figure 2 present the experimental and equipment setting. Power Meter KEW6300 used to measure the power consumed, and each single data was stored during the cutting process. Surface roughness (R_a) was measured with a Mitutoyo Surftest SJ-301 portable surface roughness tester.

Table 3. Box-Behnken design matrix.

Std Order	Input variable		
	A:Vc m/min	B:fr mm/rev	C:d mm
1	110	0.1	1.25
2	170	0.1	1.25
3	110	0.2	1.25
4	170	0.2	1.25
5	110	0.15	0.8
6	170	0.15	0.8
7	110	0.15	1.7
8	170	0.15	1.7
9	140	0.1	0.8
10	140	0.2	0.8
11	140	0.1	1.7
12	140	0.2	1.7
13	140	0.15	1.25
14	140	0.15	1.25
15	140	0.15	1.25

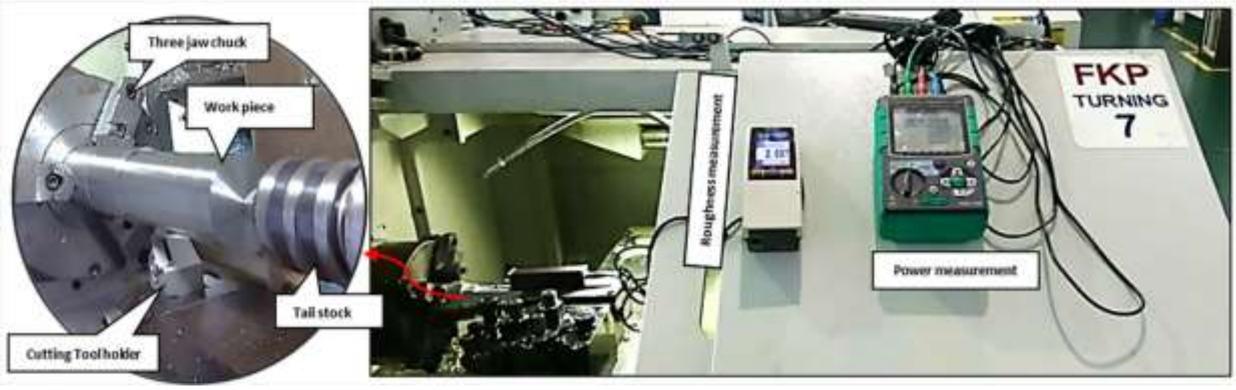


Figure 2. Experimental and instruments setting.

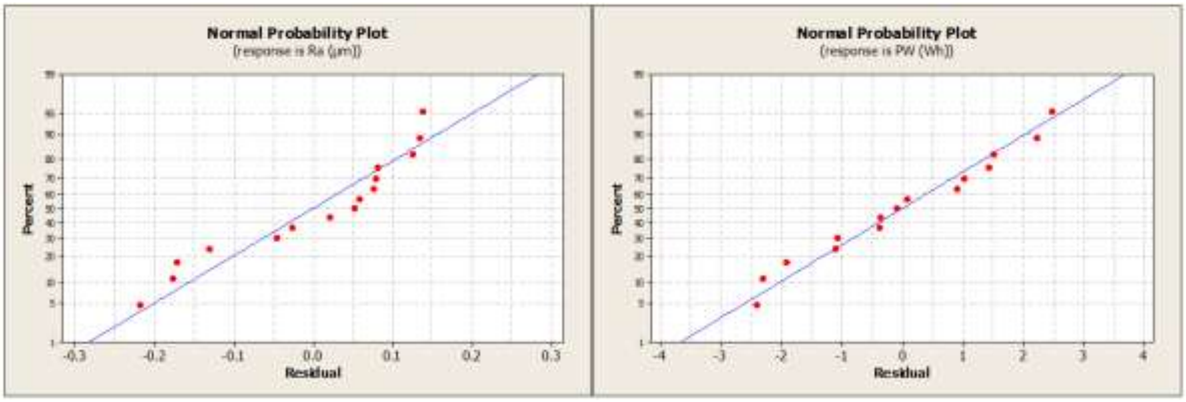
3. Results and discussion

Experimental results by BBD matrix under cooling and dry are presented in Table 4. The main and interaction effect plots for power consumption (PW, wh) and surface roughness average (Ra, µm) with respect to all cutting parameters: cutting speed (v_c, m/min), feed rate (*fr*, mm/rev) and depth of cut (d, mm) are presented in this section.

Table 4. Results of the experiment.

Std Order	Dry		Flood	
	PW (Wh)	Ra (µm)	PW (Wh)	Ra (µm)
1	32.6	0.478	41.5	0.415
2	35.51	0.965	43.87	0.534
3	25.65	0.64	34.31	0.498
4	30.28	1.331	39.2	0.987
5	34.11	0.491	32.92	0.613
6	37.8	0.924	45.79	0.528
7	23.5	1.37	32.14	1.29
8	22.81	1.104	31.52	1.467
9	36.2	0.845	45.6	0.677
10	35.72	1.245	44.32	1.245
11	32.8	1.53	42.04	1.53
12	23.9	1.6	32.56	1.225
13	27.8	0.72	36.09	0.814
14	29.81	0.714	38.13	0.726
15	26.5	0.741	34.98	0.711

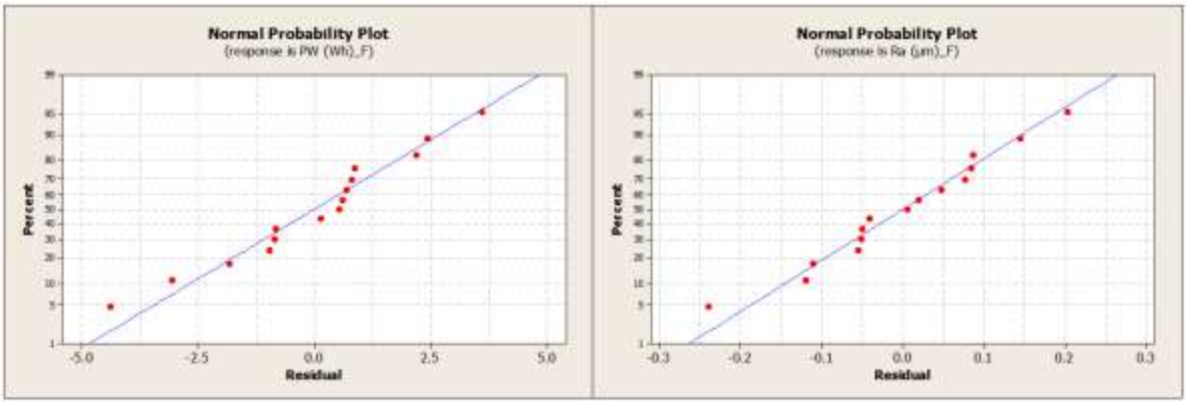
Figure 3 shows the normal probability plot for dry condition. In this plot, the residuals are tracked along the straight line, which indicates errors are normally distributed. The residuals are randomly positioned on the positive and negative side on straight line. The residuals approximately normally distributed on each side on the line and many residuals lie between -2.5 to 2.5 for power consumption and between -0.2 to 0.2 for surface roughness. Therefore, the model accepted for validation.



(a) (b)

Figure 3. Normal probability plot for dry condition (a) surface roughness (b) power.

Figure 4 shows the normal residual plot, which indicated that no outliers were found and deviations from the line were very minor. Therefore, the experiment provided a desirable value that satisfied the normality assumption.



(a) (b)

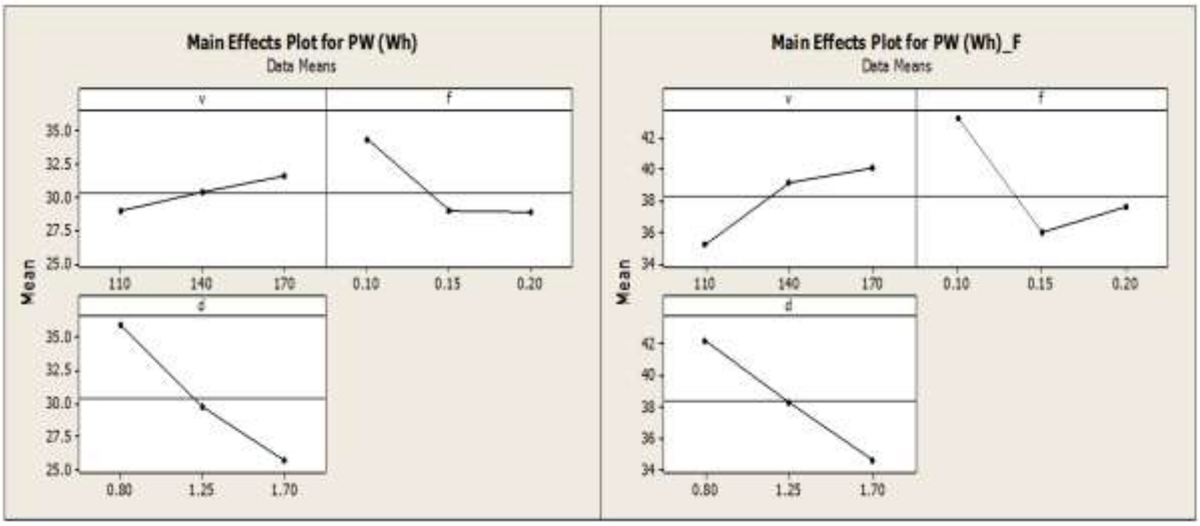
Figure 4. Normal probability plot for flood condition (a) power (b) surface roughness.

Table 5 shows the regression model and R-Squared values of power consumption and surface roughness. The mathematical functions of power and surface roughness were developed using ANOVA analysis. The results for energy consumption indicated that R^2 = 87.7% and 88% for dry and wet condition, respectively. The R- Squared for surface roughness are 86.1% and 92.6% for dry and wet, respectively. Additionally, the difference between Pred R-Squared and Adj R-Squared was less than 0.2 that indicated the models is satisfactory.

Table 5. Regression model and R-Squared values.

Regression model	R-Sq.	Adj R-Sq.	Prd R-Sq.
PW (dry)= $+5.39290-0.29426* v -0.77196 * f -0.21368* d$	0.8776	0.8546	0.7906
PW (wet) = $+5.79107-0.26496 * v -0.85629* f-0.14931 * f+0.17433* f^2$	0.8805	0.8487	0.6707
Ra (dry)= $+0.87214+0.0196 * v+0.15506 * f+0.068* d-0.0253 * v^2+0.0228 * f^2+0.0463* d^2+0.0652* v * f -0.0663 * v*d$	0.8610	0.7599	0.5631
Ra (wet) = $+0.86+0.010* v+0.14* f+0.092 * d-0.015* v^2+0.034* f^2+0.042 * v * f -0.044* v * d+0.064 * f * d$	0.9263	0.8727	0.6894

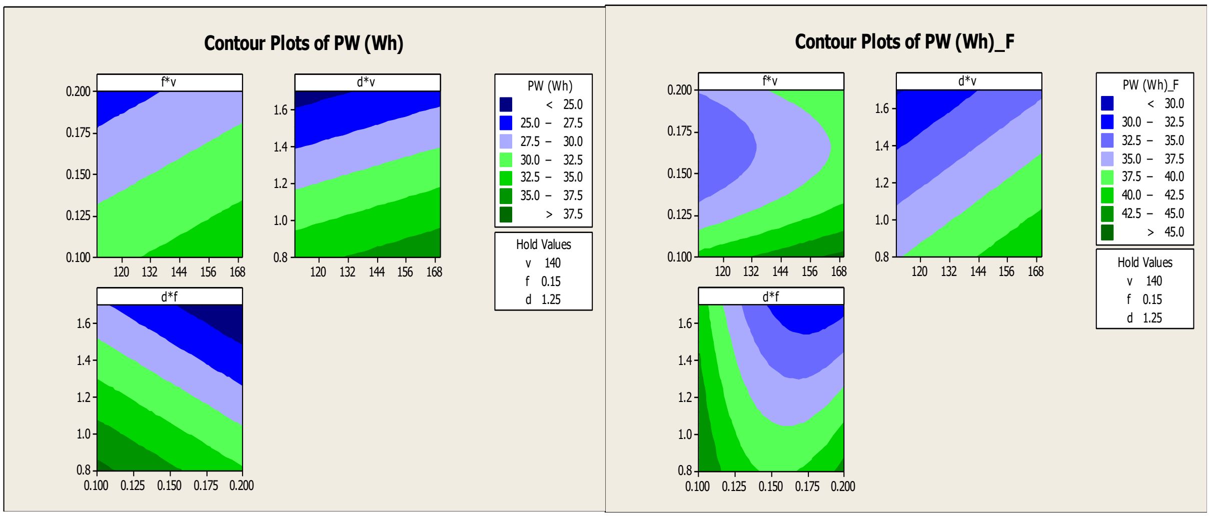
The evaluation of power consumption to machining parameters during machining are now presented. Figure 5a shows the main effects plot in indicates the mean effect of each level of parameters under dry cutting. From the plot observed that the highly-influenced factors are identified as depth of cut followed by feed rate and cutting speed. The plot for power consumption against cutting speed show a positively significant effect from low level to high level, whereas a negatively significant effect for feed rate and depth of cut. Therefore, the peak points of all independent variables as dry cutting for power consumption, 1.7mm depth of cut, feed of 0.2 mm/rev, 110 m/min cutting speed are selected. This is the optimal condition in order to minimize the power consumption to improvise the hard stainless steel turning process significantly. In Figure 5b shows the main effects plot of parameters under flood condition. It observed similar parameters influence under dry cutting with different rang of response. The high value of power consumption with use flood 42.5 Wh compare with 35 Wh under dry. The optimum points that can be achieved less power consumption are 110 m/min in cutting speed, feed rate with 0.15 mm/rev and 1.7 depth of cut.



(a) (b)

Figure 5. Main plots of power consumption (PW) versus parameters under (a) dry cutting (b) flood condition.

Figure 6 (a,b) shows contour plots of power consumption for dry and flood cutting. A counter plot of feed rate Vs cutting speed as shown in Figure 6a and the depth of cut level are kept in middle level 1.5mm. For illustration, the lowest PW was reached in the region of 0.175 to 0.2 mm/rev feed rate and 110 to 132 m/min cutting speed for dry cutting (Figure 6a), whereas from 0.135 to 0.2 mm/rev for flood condition (Figure 6b).

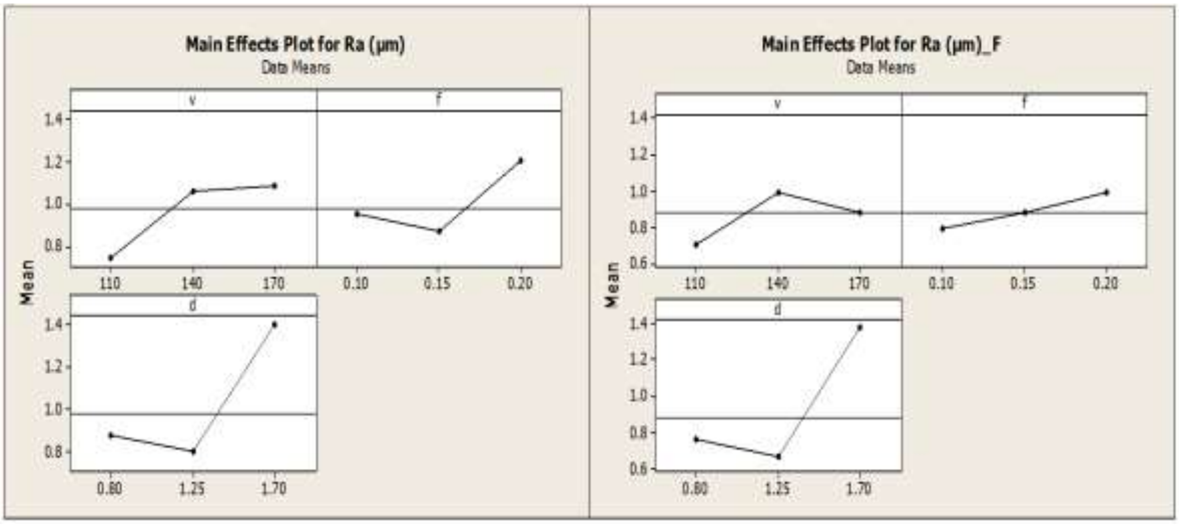


(a) (b)

Figure 6. Counter plots of power consumption (PW) versus parameters under (a) dry cutting (b) flood condition.

The contour plot of depth of cut Vs cutting speed shows the interaction effect of the depth of cut and cutting speed on the power consumption. It is seen that minimum cutting speed value and high depth of cut value facilitate to reach lower power consumption. The contour plot of depth of cut Vs feed rate shows the liner interaction effect of dry experiments (Figure 6a) and square relation under flood condition (Figure 6b) on the power consumption. The desirable region to reached minimum power consumption are (1.5-1.7 mm) depth of cut and (0.15-0.2 mm/rev) feed rate for dry cutting, and (1.6-1.7 mm) depth of cut and feed rate with (0.15-0.2 mm/rev) for flood condition.

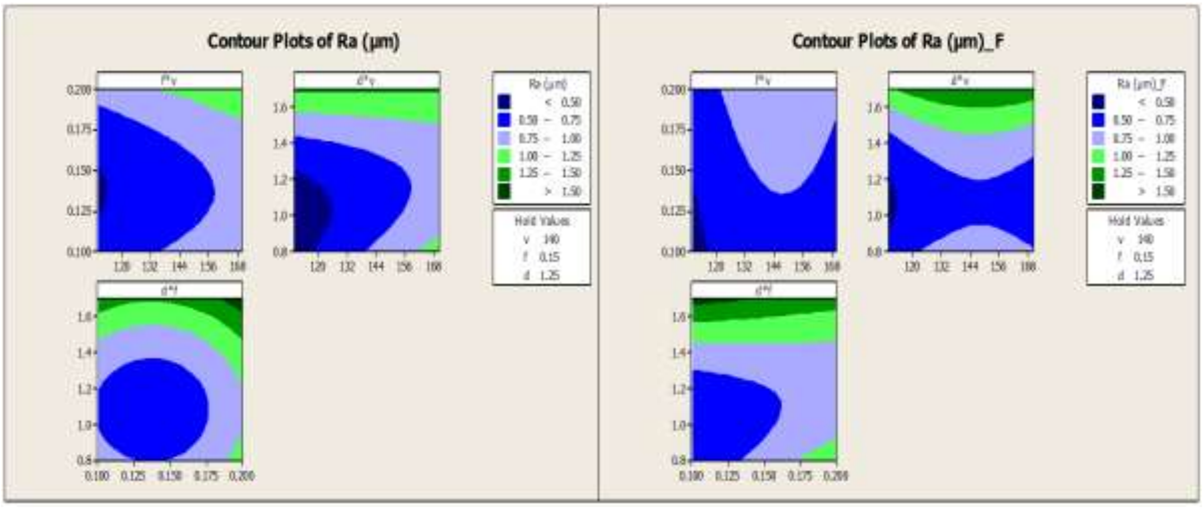
Figure 7a shows the main plot effects parameters. It can be observed from the plot that surface roughness influenced by all factors. The depth of cut was greater influence on all responses. The plot for surface roughness against factors show a positively significant effect from low to high level, there are linear relationship between surface roughness and for both cutting parameters. The optimum points of all variables to reduce surface roughness, depth of cut with 1.7mm and 110 m/min cutting speed for both condition, and feed rate of 0.15 and 0.1 mm/rev for dry and flood, respectively.



(a) (b)

Figure 7. Main plots of surface roughness (Ra) versus parameters under (a) dry cutting (b) flood condition.

Figure 8 shows contour plots of surface roughness. Generally, it is clearly the high quality of surface can be achieved when the parameters in their lower level. Figure 8a shows counter plot of feed rate Vs cutting speed with constant depth of cut value at 1.5mm. The desirable rang with minimum surface roughness for dry are 0.125 to 0.15 mm/rev of feed rate and cutting speed less than120 m/min (Figure 8a), whereas from 0.1 to 0.14 mm/rev feed and cutting speed shows small significant for flood condition (Figure 8b). The contour plot of interaction effect of the depth of cut and cutting speed on the surface roughness shows the depth of cut most significant with high range change of responses. It is seen that low value of depth of cut and cutting speed achieved lowest surface roughness for dry trials (Figure 8a), while it is slightly influence by cutting speed with flood (Figure 8b). For interaction effect of the depth of cut and feed rate, the desirable region to achieved minimum surface roughness are (0.8-1.2 µm) depth of cut and (0.5-0.15 mm/rev) feed rate for dry cutting, whereas from 0.8 to 1 mm of depth of cut and feed rate with 0.1mm/rev for flood condition.

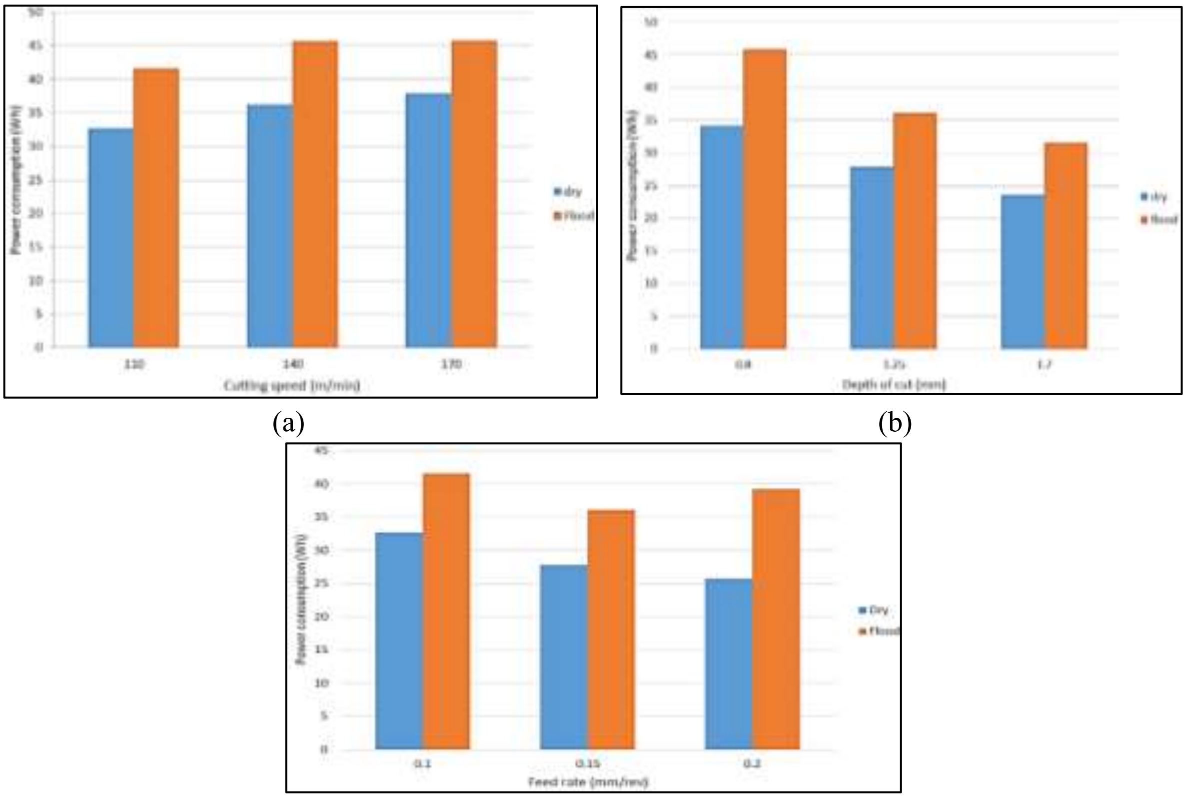


(a) (b)

Figure 8. Counter plots of surface roughness (Ra) versus parameters under (a) dry cutting (b) flood condition.

According to the statically analysis, it is found that power consumption increased with an increasing in spindle speed, whereas decreased with an increasing in both feed and depth of cut. Figure 9 shows reduce of power consumption under dry condition compare to flood during cutting stage. This increase of power consumption explained by addition power load that consumed by running coolant system.

The power consumption proportionately increase for cutting speed and decrease for others parameter (Figure 5). Increases in depth of cut and feed rate, leading to an increases the amount of removed materials and the time required to machine the workpiece decrease, subsequent decrease in power requirements for machine tool to complete the operation. Dry cutting performed better to decrease power consumption for cutting speed, feed rate and depth of cut compared to flood condition. Moreover, the compression graph (Figure 9) suggested that employing lower cutting speed with a high depth of cut and feed rate can reduce power consumption.

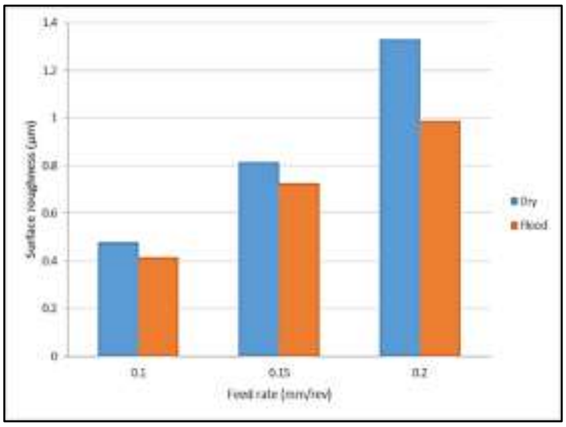


(a) (b) (c)

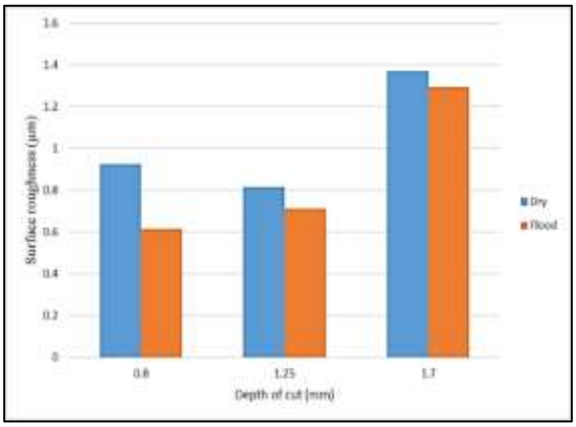
Figure 9. Power consumption versus parameters (a) cutting speed (b) depth of cut (c) feed rate.

For surface roughness evaluation, surface roughness almost increases as cutting parameter increasing for both condition (Figure 10). It is shows there is linear relationship between surface roughness and three cutting parameters. From illustrate, the coolant cutting shows better than dry cutting regarding surface roughness.

At high depth of cut, a continuous chip formed which are increase of temperature in the workpiece and tool interface which is increase friction that leads to high roughness. For dry cutting, surface roughness increase when increase of speed until reach of 140 m/min than shows not effect on surface roughness. The increase of feed rate and depth of cut shows slightly decrease of surface roughness than their relation become direct proportion with high change of roughness value. Whereas the CBN cutting tool shows better under flood condition with lowest value of feed rate. In common the surface roughness increased with the higher feed rates in all experiments. The increase of speed more the middle value lead to decrease of surface roughness. All cutting process parameters showed that machining work-piece under flood better surface finish compared to dry cutting. Higher feed rate values lead to high temperature at the tool chip interface which cause adhesion and abrasion of tools. Due to these damage of tools, the surface roughness was influenced accordingly. Due to high temperature, defect occurs rapidly at dry work-piece which causes high value of roughness. The main effect plots relations established for both cutting condition are similarly.



(a)



(b)

Figure 10. Surface roughness (Ra) versus parameters (a) depth of cut (c) feed rate.

Thus, the optimum cutting condition was found at 110 m/min cutting speed with power consumption 28.5 Wh, 35 Wh for dry and flood, respectively, and average surface roughness 0.73 µm for dry cutting, 0.69 µm under coolant. The best surface roughness and power used value are obtained at low value cutting speed. For feed rate, the optimum value under dry condition at 0.2 mm/rev with power 28.5 Wh and at 0.15 with average surface roughness 0.85 µm. For flood, the best select for feed rate at 0.15 mm/rev with power consumption 37.8 Wh and at 0.1with 0.79µm average surface roughness. The optimum power consumption at the high depth of cut 1.7 mm with 25.5 Wh of power consumption and 0.8 µm for average surface roughness at 1.25 mm. With high value of power consumption (35 Wh) and less value of the surface roughness (0.67 µm) for wet condition. Considering both responses, it can be concluded the performance of CBN insert under dry cutting condition can be minimize the power consumption with acceptable quality. It is a good technique of environmental machining without fluids impact. The optimum parameters selected help to reduce the effect of issues associated with the dry machining such are tool life, cutting temperatures and thermal damage to the workpiece.

4. Conclusions

The performance of CBN inserts and comparison study between dry and wet cutting stainless steel on minimum value of energy and surface roughness was evaluated. The results indicated that stainless still can be machined under dry condition with low power consumption and acceptable quality when compared wet cutting. The plot graphs clearly show for both condition dry and wet that the minimum value of energy consumption of the cutting process was obtained at the lowest cutting speed value and at the high values of feed rate and depth of cut. The factor with the most significant influence on surface roughness was feed rate. Results also showed an improvement of power consumption under dry condition 18.57%, whereas for surface roughness showed coolant slightly better with 1.45% than dry cutting. The CBN tools under dry cutting can be used to reduce the environment impacts in terms of no cutting fluid use and less energy required which is affected in machining productivity and profit.

Acknowledgments

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