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Effect of Cutting Parameters on the Surface Roughness Generated During Face Milling Of Pearlitic Ductile Iron with Cemented Carbide Tool

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ABSTRACT

This study examined the effect of cutting parameters on the surface roughness generated during face milling operation of a pearlitic ductile iron using cemented carbide tool. The pearlitic ductile iron used for the study was prepared from scraps of ferrous metals using 100 kg rotary furnace at the Engineering Materials Development Institute (EMDI), Akure, Nigeria. Four cutting parameters were considered for the study, namely; cutting speed, feed rate, depth of cut and cutting fluid flow rate. The experimentation was based on Taguchi's design approach. The data collected were subsequently subjected to analysis of variance. The average surface roughness of machined surfaces, increased as depth of cut increased. The effect of increase in feed rate and cutting speed was to reduce the average surface roughness, though not statistically significant. On the other hand, surface roughness decreased significantly with increase in cutting fluid flow rate and depth of cut. The average surface roughness value was highest at zero fluid flow rate and lowest at the flow rate of 4 l/min. The study concluded that out of all four cutting parameters investigated, the cutting fluid flow rate had most considerable positive influence on the surface roughness of a machined pearlitic ductile iron.

Keywords: *Surface Roughness, Cutting Parameters, Face Milling, Pearlitic Ductile Iron.*

1. INTRODUCTION

Surface integrity is the sum of all elements that describe the conditions existing on the surface of a finished hardware. It is built up by the geometrical values of the surface such as surface roughness and the physical properties such as residual stresses, hardness and structure of the surface layers [1]. These properties are critical to the functionality of machined components. Thus, a good understanding of surface generation mechanisms can be used to optimize machining processes and thereby improve component functionality. The demand for high quality and fully automated production focuses attention on the surface condition of the product, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability. For these reasons, it is important to maintain consistent tolerances and surface finish [2]. A number of factors influence the final surface roughness in end milling operation. Factors such as spindle speed, feed rate and depth of cut that control the cutting operation can be setup in advance. However, factors such as tool geometry, tool wear, and chip formation, or the material properties of both tool and workpiece are uncontrolled [2]. Numerous investigations have been conducted to determine the effect of parameters such as feed rate, tool nose radius, cutting speed and depth of cut on surface roughness in turning operations [3]. These investigations show consistently that the surface roughness is predominantly a function of the feed rate. Arunachalam *et al.* [4] studied the surface roughness generated when facing age hardened Inconel 718 using cubic-boron-nitride (CBN) cutting tools as a function of cutting speed, depth of cut and coolant. They reported that the values of surface roughness decreased with increase in the cutting speed, the coolant used generated good surface roughness that is free from deposited built-up edges and lower depth of cut resulted in better surface roughness. Also, Hayajneh *et al.* [2] studied the effect of machining parameters (spindle speed, cutting feed rate and depth of cut) on the surface roughness in the end milling process. They observed that cutting feed rate is the most dominant factor that influenced the surface finish of the machined workpiece significantly. Kuram *et al.* [5] investigated the effect of different types of cutting fluid and cutting parameters on surface roughness and thrust force during drilling of AISI 304 austenitic stainless steel using HSS tool. They reported that increase in the spindle speed decreased the surface roughness value and the thrust force value; an increase in the feed rate increased the surface roughness and the thrust force values. They also observed that the cutting fluids used were effective in reducing surface roughness and thrust force as spindle speed increased at the lowest feed rate. Yusuf *et al.* [6] also conducted a research on the effect of cutting parameters on the surface roughness of titanium alloys using end-milling process. They employed the Taguchi design method to optimize the surface roughness quality in a computer numerical control (CNC) end mills. Their experimental results indicated that spindle speed is the most significant factor affecting the surface roughness quality and tool life, followed by type of end mills tool, feed rate and depth of cut in that order. Rech and Moisan [7] studied the influence of feed rate and cutting speed on the surface roughness of case-hardened 27MnCr5 steel in hard turning. In their study, the feed rate was the main parameter that influenced the surface roughness compared to the influence of cutting speed. The hard turning process is interesting with regards to its capacities to produce a low surface roughness during a long cutting time. Gunnberg *et al.* [8] studied the influence of cutting parameters like tool rake angle, tool nose radius, cutting speed, cutting depth and feed rate on surface topography during hard turning of 18MnCr5 case carburized steel using poly cubic-boron-nitride (PCBN) cutting tool inserts. They reported from their study that the surface roughness values were mainly influenced by the feed rate and tool nose radius. Also, Jacobson *et al.* [9] examined the effect of cutting speed on surface roughness in the hard turning of bainite steel B8. They reported that increase in the cutting speed increased the surface roughness. At low cutting speed the surface roughness was found to be minimum. This study examined the effect of some machining parameters on the surface roughness generated in the face milling of locally produced pearlitic ductile iron.

2. MATERIAL AND METHODS

2.1.Material preparation

The pearlitic ductile iron used for this study was cast at Engineering Materials Development Institute (EMDI), Akure, Ondo state, Nigeria, using a rotary furnace of 100 kg capacity designed and built by the Institute. Small sample of castings obtained was appropriately ground and polished with the SBT Model 900 and Metaserv 2000 grinder/ polisher with emery paper grits 60, 120, 240, 320, 400 and 600, for metallographic examination. The etchant was prepared from 2% nitric acid and 98% alcohol (Nital). Nikon Eclipse ME600 metallurgical microscope of x200 magnification was used to carry out the microstructural examination. The micrograph (Figure 1) shows ductile iron containing nodular graphite in a matrix of pearlite with small amount of ferrite at 500 magnification (500x). The chemical composition of the pearlitic ductile iron as obtained with EDS (Energy Dispersive Spectrometer) analysis is shown in Table 1; its mechanical properties were obtained using Nano-indenter and are shown in Table 2. Table 1 shows that the material is iron rich with 93.17% iron, 3.6% carbon, 2.9% silicon, 0.25% manganese, 0.025% sulphur, 0.01% magnesium and 0.045% phosphorus. This is similar to ASTM A536 100-70-03 specification for pearlitic ductile iron. Castings of the pearlitic ductile iron which were retrieved from the moulds after cooling to room temperature were sectioned with a power hacksaw. All sectioned castings were subjected to annealing heat treatment by heating to temperature of 650ºC, holding at this temperature for four hours and furnace-cooling to relieve all residual stresses induced during the casting process.

2.2. Face milling tests

The face milling tests were carried out at Engineering Materials Development Institute (EMDI), Akure, Ondo State, Nigeria, using cemented carbide cutting tool (Grade YG6 and Type 4160511) and soluble oil as cutting fluid. A 3-axis CNC vertical machining centre (PRODIS PDC-650H machine centre) with spindle speed up to 10,000 rpm and power output of 15kVA was used for the test. Four cutting parameters were considered for the experimentation, namely; depth of cut, feed rate, cutting speed and cutting fluid flow rate. Five levels were assigned to each parameter. Taguchi's experimental design approach was used to drastically reduce the number of experimental runs required because it uses special design of orthogonal arrays to study the entire parameter space with a small number of experiments.

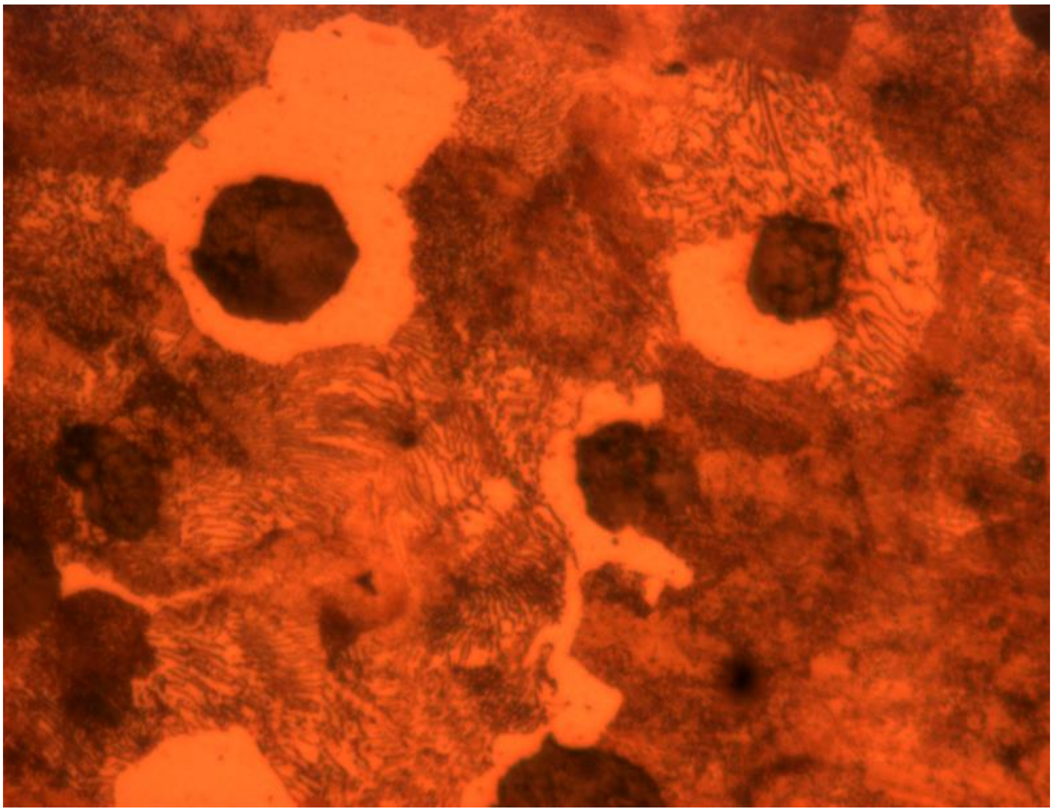

Figure 1: Micrograph of as-cast Pearlitic Ductile Iron showing Graphite Nodules (x500)

Table 1: The Chemical Composition of the Pearlitic Ductile Iron

Elements	% (Weight)
C	3.6
Si	2.9
Mn	0.25
S	0.025
Mg	0.01
P	0.045
Fe	93.17

Table 2: The Mechanical Properties of the Pearlitic Ductile Iron

Properties	Value (Unit)
Hardness (BHN) (AVG)	277
Tensile Strength	690 MPa
Yield Strength	483 MPa
Elongation	3 %

*BHN – Brinell Hardness Number
*AVG – Average

Table 3 shows the levels of cutting parameters considered and how they were combined in accordance with Taguchi's design to obtain the 25 experimental runs used for this study. Nano-indenter with Atomic Force Microscope (AFM) compartment was used to examine the surface roughness of the machined parts without indentation (see Appendix). The data collected were subjected to analysis of variance (ANOVA).

3. RESULTS AND DISCUSSION

The values of surface roughness generated during the face milling operation at various combinations of values of cutting parameters used in this study are presented in Table 4. Statistical analysis established that the effect of feed rate and cutting speed were not significant on the surface roughness. ANOVA and Duncan multiple range test established that depth of cut and cutting fluid flow rate have statistically significant influence on the average surface roughness generated (Table 5).

3.1. Effect of feed rate on surface roughness

The effect of feed rate on the surface roughness generated during face milling operation was not statistically significant. Figure 2 shows how the surface roughness varies with feed rate at the average cutting speed, cutting fluid flow rate and depth of cut values of 1000 rev/min, 2 l/min and 0.6 mm respectively; it shows no definite trend. It is obvious from the Figure that the variation observed is merely a random one that may be due to experimental error. Grzesik and Zak [10] stated that for higher feed rate, surface roughness produced by oblique turning is substantially lower than that generated by lower feed rate. Their observation was thought to be due to high milling cutter vibration and tool wear rate caused by low feed rate. This disagreed with reports of Navas *et al.* [11], Bajic *et al.* [12] and Rech and Moisan [7] who reported increase in the surface roughness as feed rates increased. They emphasized that feed rate is the main factor influencing the surface roughness, due to the geometrical relations between the feed, tool nose radius and roughness in turning operations. However, in machining operations, other cutting parameters also influence surface roughness, because of the material behavior under large deformations.

Kuram *et al.* [5] also reported that an increase in the feed rate increased the surface roughness values since an increase in feed rate increased the materials removal rate. Also, Hughes *et al.* [13] showed that an increase in feed rate resulted in a larger surface roughness value due to more feed marks. Similarly, Thiele and Melkote [3], and Franco *et al.* [14] also stated that the more the increase in the values of feed, the more the surface deteriorates in face milling with round insert cutting tools. These observations are at variance with the result of this study perhaps because the feed rate values used in this work are much larger than those used in the earlier studies.

Table 3 Combination of the Cutting Parameters used for Experimentation

Experimental Run	Factors			
	Depth of Cut (mm)	Feed Rate (mm/rev)	Cutting Speed (rev/min)	Cutting Fluid Flow Rate (l/min)
1	0.2	10	200	0.0
2	0.2	20	600	1.0
3	0.2	30	1000	2.0
4	0.2	40	1400	3.0
5	0.2	50	1800	4.0
6	0.4	10	600	2.0
7	0.4	20	1000	3.0
8	0.4	30	1400	4.0
9	0.4	40	1800	0.0
10	0.4	50	200	1.0
11	0.6	10	1000	4.0
12	0.6	20	1400	0.0
13	0.6	30	1800	1.0
14	0.6	40	200	2.0
15	0.6	50	600	3.0
16	0.8	10	1400	1.0
17	0.8	20	1800	2.0
18	0.8	30	200	3.0
19	0.8	40	600	4.0
20	0.8	50	1000	0.0
21	1.0	10	1800	3.0
22	1.0	20	200	4.0
23	1.0	30	600	0.0
24	1.0	40	1000	1.0
25	1.0	50	1400	2.0

Table 4 Effect of the cutting parameters on the surface roughness generated during face milling of the pearlitic ductile iron

Depth of Cut (mm)	Feed Rate (mm/rev)	Cutting Speed (rev/min)	Cutting Fluid Flow Rate (l/min)	Surface Roughness RMS (nm)
0.2	10	200	0	101.78
0.2	20	600	1	66.25
0.2	30	1000	2	49.63
0.2	40	1400	3	20.07
0.2	50	1800	4	18.98
0.4	10	600	2	64.47
0.4	20	1000	3	30.41
0.4	30	1400	4	21.73
0.4	40	1800	0	102.92
0.4	50	200	1	90.28
0.6	10	1000	4	40.05
0.6	20	1400	0	107.77
0.6	30	1800	1	95.71
0.6	40	200	2	56.91
0.6	50	600	3	50.47
0.8	10	1400	1	97.66
0.8	20	1800	2	69.66
0.8	30	200	3	61.39
0.8	40	600	4	51.13
0.8	50	1000	0	132.85
1.0	10	1800	3	75.16
1.0	20	200	4	47.00
1.0	30	600	0	154.70
1.0	40	1000	1	101.94
1.0	50	1400	2	96.26

Table 5 ANOVA for surface roughness

Factors	Degree of Freedom	Sum of Squares	Mean Square	Variance	Percentage Contribution (%)
Depth of Cut	4	5856.032	1464.008	54.11	19.06
Feed Rate	4	794.590	198.647	7.34	2.59
Cutting Speed	4	1202.059	300.515	11.11	3.91
Cutting Fluid Flow Rate	4	22875.625	5718.906	211.32	74.44
Residual (Error)	8	216.451	27.061	-	-
Total	24	30728.306	-	-	-

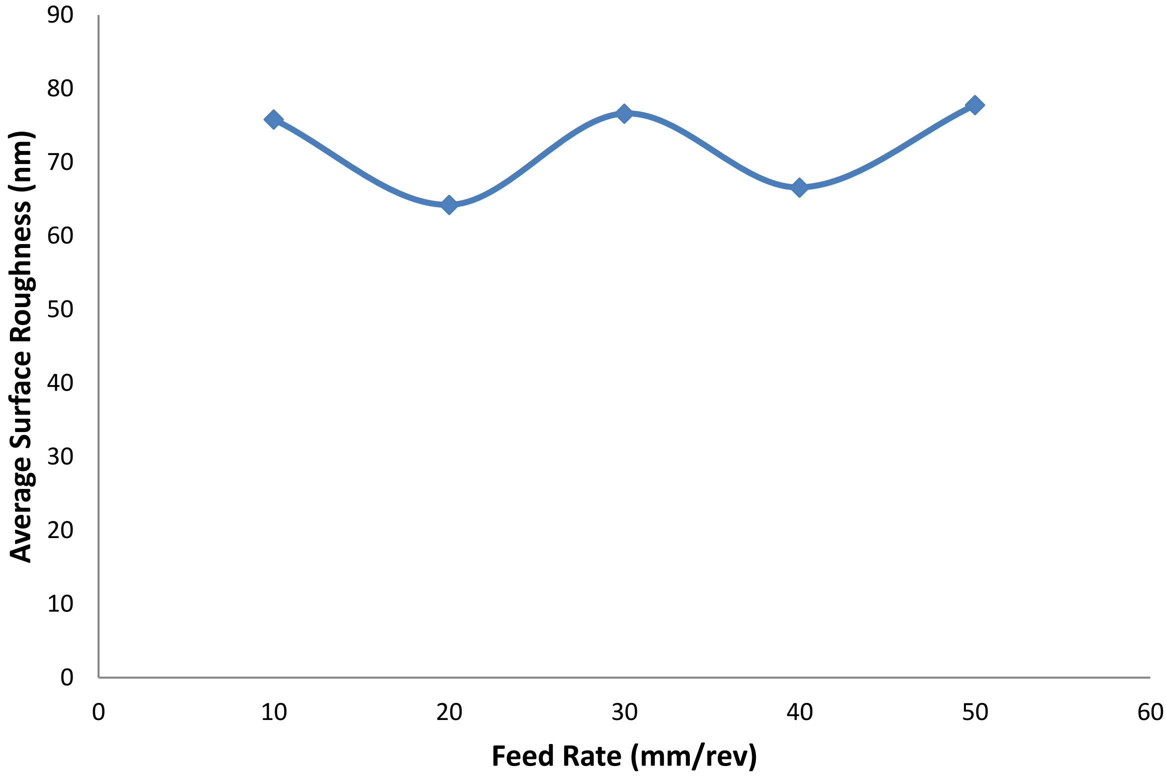

Figure 2: Observed variation of average Surface Roughness with feed rate

3.2. Effect of cutting speed on surface roughness

Figure 3 illustrates the variation in the surface roughness with increase in cutting speeds at average depth of cut, feed rate and cutting fluid flow rate values of 0.6 mm, 30 mm/rev and 2 l/min respectively. The variation has no definite trend and it is therefore not statistically significant. The average surface roughness increased as cutting speed increased from 200 – 600 rev/min and decreased between cutting speeds of 600 and 1400 rev/min. As cutting speed increased beyond 1400 rev/min, the surface roughness increased again. Across all speeds, the range of surface roughness variation is quite narrow (68.69 – 77.40 nm) and appears more or less like a random variation; indeed, ANOVA established that it is statistically insignificant at 5% significance level. Lopez de lacalle *et al*. [15] reported that with the increase of cutting speed, surface roughness value first increased and then decreased with the tool wear progression in milling using hard solid mills.

On the other hand, Uyaner *et al*. [16] observed in machining of ADI (Austempered Ductile Iron) that the surface roughness values decreased with increasing cutting speed until a limit (1400 rev/min) when it started to increase. This appears to agree perfectly with the results observed in this study in the speed range, 600 – 1800 rev/min. The observed increase in the surface roughness as speed increased from 1400 – 1800 rev/min could be attributed to the possible increase in tool wear at high cutting speeds. The temperature in the cutting area increased with increasing cutting speed and for a cutting process maintained at a raised temperature, the strength of the built-up edge is reduced. The temperature on the tool face also played a major role with respect to the size and stability of the built-up edge [16]. An earlier study by Yigit *et al*. [17] on the effect of cutting speed on the performance of multilayer-coated cutting tools when turning nodular cast iron reported a similar trend. Bajic *et al*. [12] who modeled machined surface roughness in face milling process also reported that minimum surface roughness could be achieved by setting the cutting speed as high as possible. This was inconsistent with the trend observed by Rech and Moisan [7] who reported from their experimental study on the turning of case-hardened steel that cutting speed has a small influence on finishing operations. Furthermore, Axinte and Dewes [18] who studied high speed milling of hot worked tool steel also reported that the values of surface roughness increased when cutting speed increased. They notted that this is contrary to what would normally be expected because higher cutting speeds generally give lower roughness due to avoidance of built-up edge effect. As no built-up edge was seen on the cutting tool and workpiece, the increase, according to them, was due to increased unbalance of the cutting tool inserts at high cutting speed, with possible vibrations in the milling cutter and tool wear.

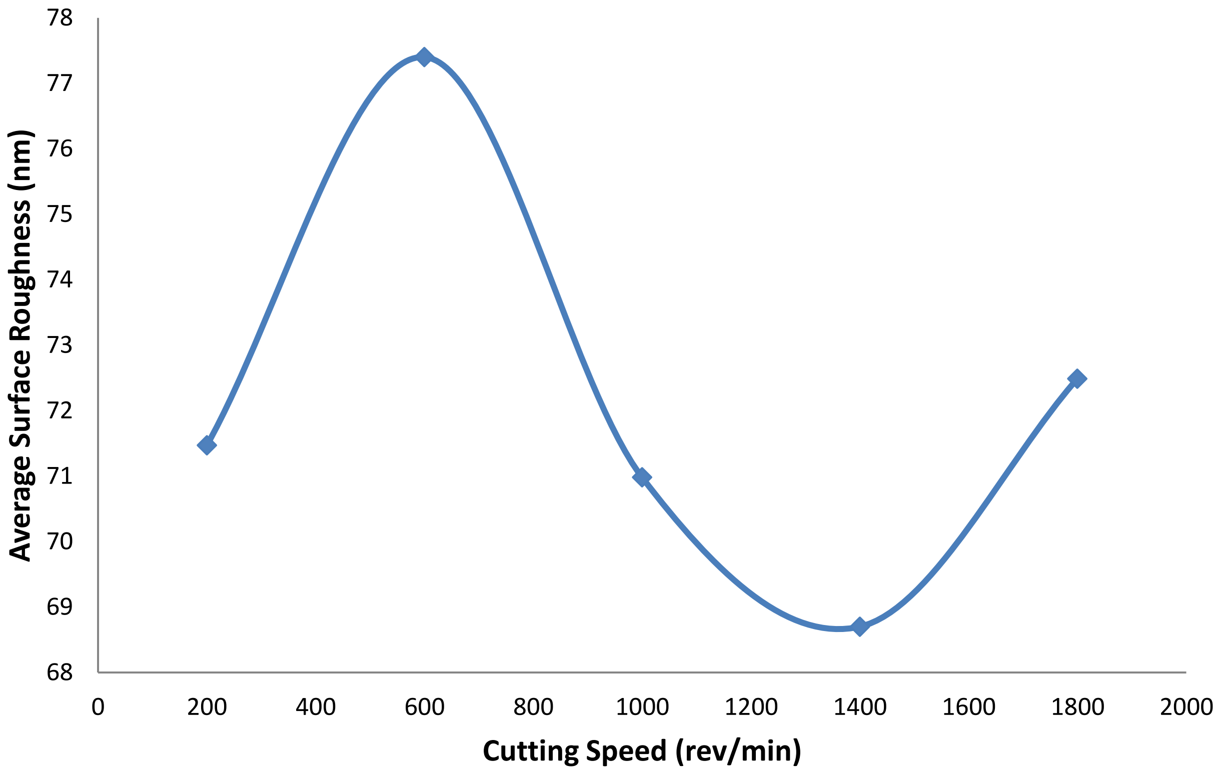

Figure 3: Variation of average Surface Roughness with cutting speed

The seemingly irreconcilable inconsistencies in the results reported by various researchers is probably a pointer to the fact that the integrity of the surface generated in machining operations may depend largely on the workpiece and tool material types. The complex material-variable physico-chemical interactions between the workpiece and tool at the elevated temperatures associated with high speed machining operations is perhaps a significant determinant of the properties of the workpiece surface generated.

3.3. Effect of depth of cut on surface roughness

Figure 4 shows the effect of depth of cut on the surface roughness of machined workpieces at the average feed rate, cutting speed and cutting fluid flow rate values of 30 mm/rev, 1000 rev/min and 2 l/min respectively. The surfaces of machined samples became significantly rougher as depth of cut increased. This result agrees with the observations of Uyaner *et al*. [16].

The result is also consistent with an earlier report by Arunachalam *et al*. [4] who studied the residual stress and surface roughness generated when facing age hardened Inconel 718. Sosa *et al*. [19] also observed that roughness increased as depth of cut increased in machining of thin wall ferritized ductile iron plates. This is probably because increased cutting force and tool wear results from the increase in depth of cut. The increased cutting forces cause several changes in the shapes of both tool and workpiece and probably change the location (position) of tool/workpiece thereby affecting cutting quality [16] and increasing workpiece surface roughness. On the other hand, Bajic *et al*. [12] reported from modeling of machined surface roughness that depth of cut has a negligible influence on surface roughness.

Figure 5 illustrates the variation in surface roughness with depth of cut at various levels of fluid flow rate. It reveals that the upper and lower limits of the range of variation in surface roughness observed in this study decreased with increase in fluid flow rate. For instance, at fluid flow rate of 0 l/min (dry cutting), the roughness value increased from 101.78 – 154.70 nm as depth of cut increased from 0.2 – 1.0 mm. At fluid flow rate of 4 l/min (wet cutting), the roughness value increased from 18.98 – 47 nm as depth of cut increased from 0.2 – 1.0 mm.

3.4. Effect of cutting fluid flow rate on surface roughness

Figure 6 shows the effect of cutting fluid flow rate on the surface roughness of machined surfaces at average depth of cut, feed rate and cutting speed values of 0.6 mm, 30 mm/rev and 1000 rev/min respectively.

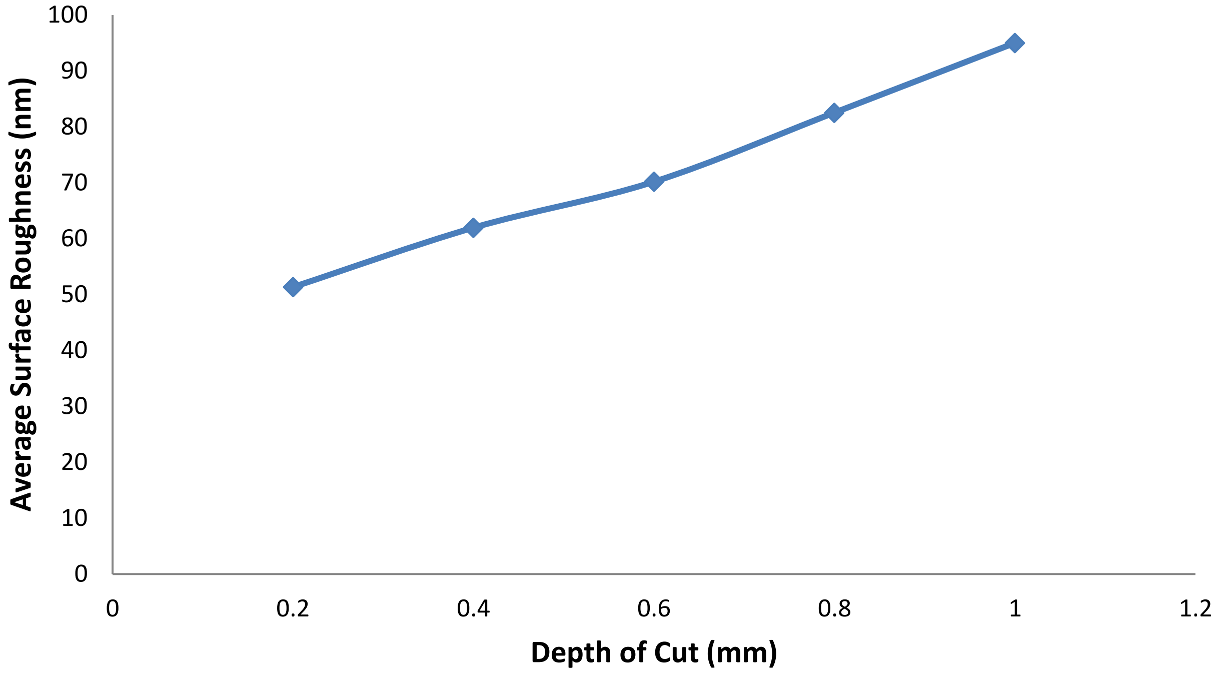

Figure 4: Effect of Depth of Cut on Average Surface Roughness

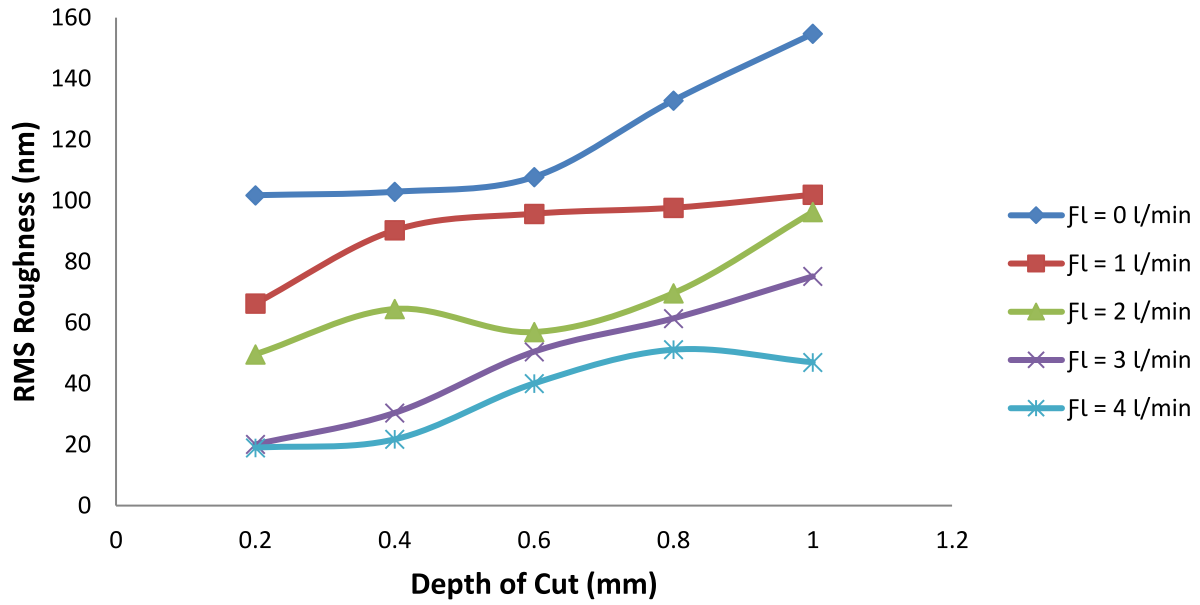

Figure 5: Effect of Depth of Cut on Surface Roughness at various levels of Cutting Fluid Flow Rate

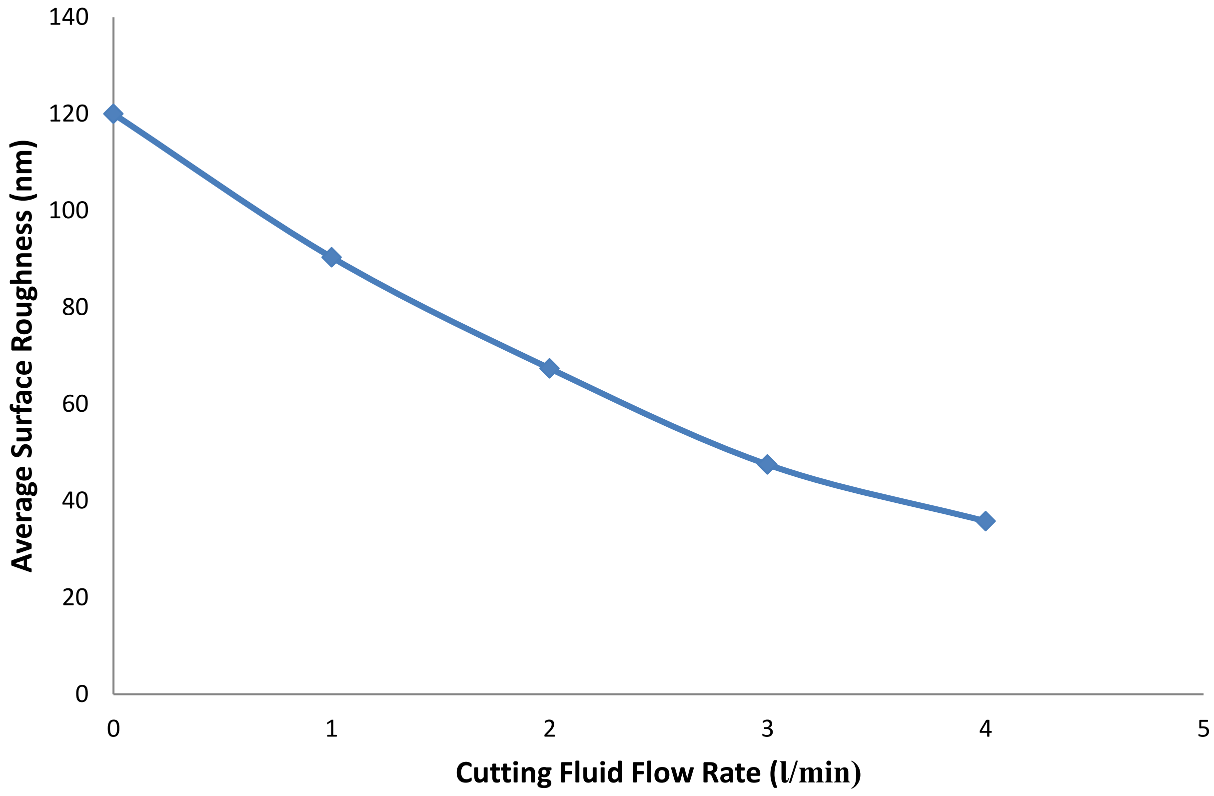

Figure 6: Effect of Cutting Fluid Flow Rate on Average Surface Roughness

The surface roughness decreased significantly with increase in cutting fluid flow rate at 5% significance level. The average surface roughness value was highest at fluid flow rate of 0 l/min (dry machining) and lowest at the flow rate of 4 l/min. This shows that machining at dry condition increased the surface roughness thereby generating a poor surface finish while machining at wet conditions reduced surface roughness thereby producing a good surface finish. It is observed from Figure 6 that the average surface roughness decreased from 120.00 – 35.78 nm as cutting fluid flow rate increased from 0 – 4 l/min. This agreed with Arunachalam *et al.* [4] who reported that low values of surface roughness were obtained when coolant was used while dry cutting resulted in high values of surface roughness. The higher values of surface roughness in dry cutting were due to the built-up edges deposited over the machined surface and the higher temperature involved. But as the cutting fluid was applied, the surface roughness values dropped because of the reduction in the temperature on the machined surface during machining and this result in a smoother finish. The use of cutting fluid also generates good surface that is free from deposited built-up edges [4]. Zhou *et al.* [20] observed that machined surfaces produced using cutting fluid were superior to corresponding surfaces generated under dry cut condition. Kuram *et al.* [5] also found that vegetable based (sunflower) cutting fluid reduced the surface roughness effectively in machining process. Dhar *et al.* [21] reported that the cutting performance of minimum quantity lubrication (MQL) machining was better than that of dry machining because it provided better surface finish in cutting process. It provided the benefits by reducing the cutting temperature which improved the chip – tool interaction and maintains sharpness of the cutting edges.

Figure 7 shows how the surface roughness varies with fluid flow rate at various levels of depth of cut, the other parameter that had significant effect on the surface roughness. It shows that the upper and lower limits of the range of variation in surface roughness with fluid flow rate increased with increase in depth of cut. For instance, at depth of cut of 0.2 mm, surface roughness decreased from 101.78 – 18.98 nm as cutting fluid flow rate increased from 0 – 4 l/min while at depth of cut of 1.0 mm, roughness decreased from 154.70 – 47.00 nm as fluid flow rate increased from 0 – 4 l/min.

On the contrary, Yusuf *et al.* [6] stated that coolant did not significantly affect the surface roughness quality during machining. Ezugwu *et al.* [22] also observed that surface roughness was not affected by coolant pressure. However, these observations could hardly be scientifically explained.

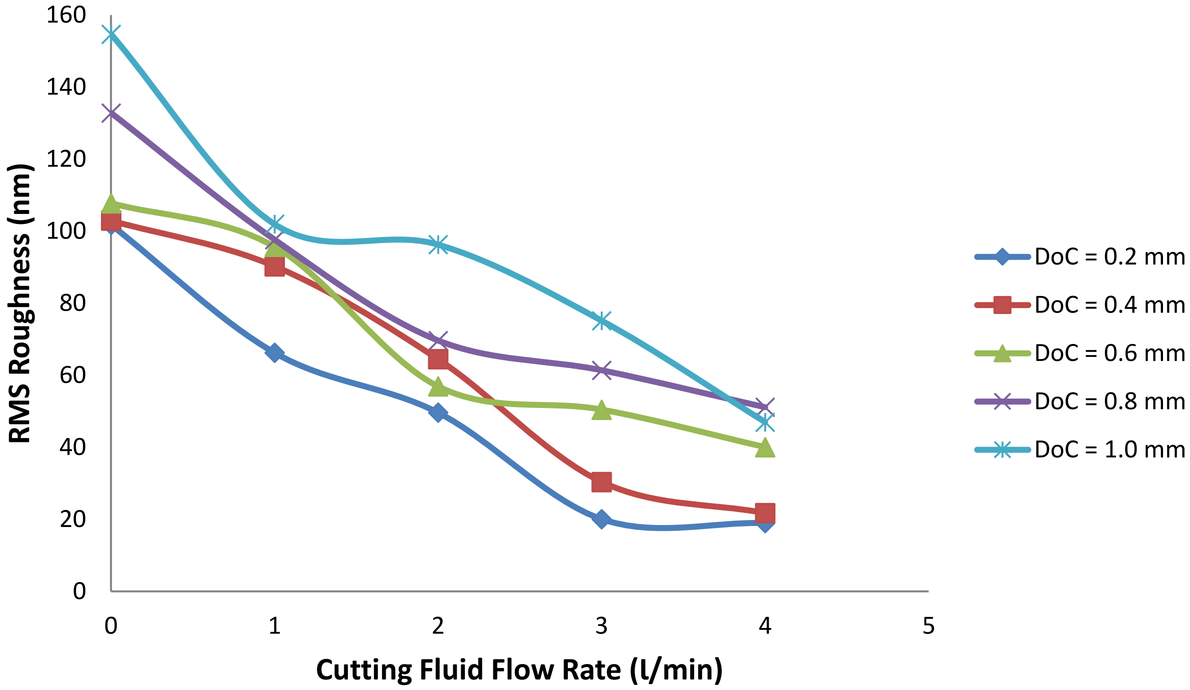

Figure 7: Effect of Cutting Fluid Flow Rate on Surface Roughness at various levels of Depth of Cut

4. CONCLUSION

The study concluded that all the four (4) cutting parameters studied have some effect on surface roughness of the pearlitic ductile iron face-milled with cemented carbide cutting tool. The surface roughness was statistically significantly affected by cutting fluid flow rate and depth of cut while the effect of feed rate and cutting speed on the surface roughness were not statistically significant ($p \leq 0.05$).

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