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Effect of Process Parameters on Surface Roughness in HPC Drilling of AISI 1055 Steel

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ABSTRACT

Data regarding the influence of high-pressure coolant on the performance of drilling process using design of experiment has been limitedly available. This paper presents the effect of higher coolant pressures along with spindle speed, feed rate and peck depth on the surface roughness of hole using Taguchi technique. Experimental set up was developed consisting of specially manufactured high-pressure coolant system and high-pressure adapter assembly attached to vertical machining center. Developed experimental set up has optimized utilization of non-through coolant vertical machining center in a small-scale industry. Experiments were conducted on AISI 1055 steel with TiAIN coated drill on the vertical machining center. Taguchi technique was used for design of experiment and analysis of results. Results revealed that the surface roughness improve till coolant pressure reaches to an optimum value of 13.5 bar and there after it decreases. Coolant pressure and spindle speed was the significant process parameters for the hole surface roughness. Surface roughness at the top of hole was considerably lower than the bottom of hole, under the action of all process parameters. Supply of coolant at high pressure has resulted in lower surface roughness even with large peck depth; which indicate that, manufacturing cost can be reduced with the use of high-pressure coolant in drilling.

Keywords: *High Pressure Coolant (HPC); High Pressure Coolant System; Adapter Assembly; Taguchi Method*

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Introduction

High pressure cooling, cryogenic cooling [1,2] and atomized coolant spray [3,4] are the most focused trends in the manufacturing research [5].Various researchers have studied the high-pressure coolant machining. Lopez de Lacalle et al. [6] studied the influence of HPC in drilling of Inconel 718 and Ti6A14V. HPC drilling with internal coolant showed better tool life than the conventional coolant drilling, even at high cutting speeds. Dhar et al. [7] concluded that HPC drilling results in lesser roundness deviation. Bermingham et al. [8] conducted drilling experiments on Ti-6Al-4V with WC-Co drill at 70 bar coolant pressure and concluded that the productivity and tool life was substantially improved with HPC.

Jessy et al. [9] investigated the influence of coolant supplied in the range of 0.01 to 0.03 bar pressure and revealed that, internal coolant drilling results in considerable reduction of drill temperature than the external coolant drilling. Bagci and Ozcelik [10] studied the impact of an internal air coolant supplied at 1 bar and 3 bar pressure and revealed that, the coolant pressure has greater influence on the drill temperature. Li et al. [11] analyzed drilling of Ti alloy with spiral point drill at 2 bar coolant pressure. The study emphasized the scope for research work in HPC drilling. Shete and Sohani [12] showed that the drilling at the bottom of hole was more critical that the top of hole. D’Addona and Raykar [13] concluded that, coolant pressure has a considerable influence on the tool temperature and higher coolant pressure results in efficient cooling and effective lubrication action at the cutting zone. Tanabe and Hoshino [14] developed a new forced cooling technology for machining difficult-to-machine material and concluded that the technology effectively cools the tool tip and removes the chips. Arunkumar et al. [15] investigated effects of deep hole drilling parameters on the hole quality and concluded that the coolant pressure, spindle speed are the significant parameters affecting on the surface roughness, circularity and cylindricity of hole. Oezkaya and Biermann [16] investigated the velocity, kinetic energy and distribution of coolant oil at the cutting edges and in the clearance between tool flute and work piece in deep drilling process of AISI 316L. The study concluded that heat generated between tool, work piece and chip cannot be removed satisfactorily, due to reduced flow velocity of coolant during drilling.

The literature survey revealed that, study pertaining to the HPC drilling has been limited to the use of a constant high-pressure coolant and pinpointed on the necessity of investigation on the effect of HPC in drilling process using design of experiment [17]. Hence, present study aims to determine the effect of variation of high pressure of coolant, spindle speed, feed rate and peck depth on the surface roughness of hole in drilling using Taguchi Technique. The present work involves the development of an experimental set up, so as to boost the productivity in small scale industries.

The investigation has been performed to obtain the optimal process parameters of drilling process, which results in reduced surface roughness and manufacturing cost.

Experimental Set Up

Drilling operation constitutes, drilling throughout holes of diameter 10 mm and depth 55 mm in AISI 1055 steel workpieces of Ø 20x55 mm dimension. The specifications of solid coated carbide drill [18] are shown in Table 1. Semi synthetic coolant was selected, as it is widely used in manufacturing industries. Specifications of the coolant are shown in Table 2.

The selected VMC was of low coolant pressure-non through coolant type category. Hence a specially manufactured high-pressure coolant system and high-pressure adapter assembly was attached to this machine, as shown in Figure 1. The HPC system develops and supply high pressure coolant to adapter assembly and thereafter adapter assembly supply this coolant to the through coolant drill.

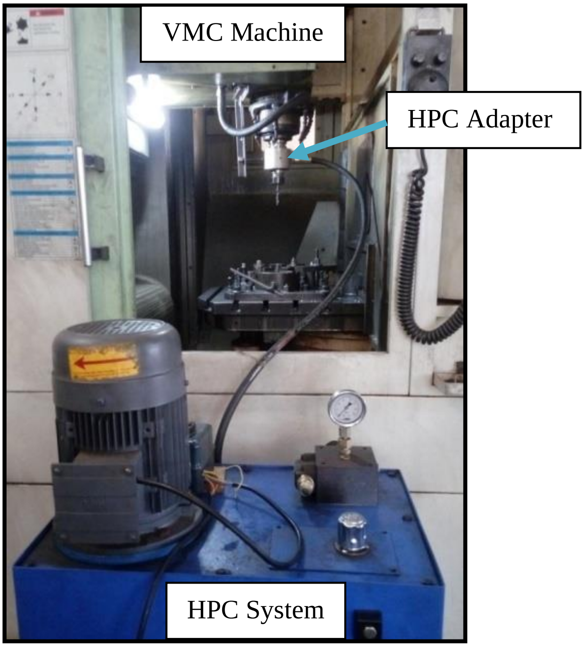


Figure 1: Experimental set up

The experimental set up was developed specially for the VMC machines, which are not having inbuilt through coolant drilling or milling facility. Thus, it optimizes the utilization of existing non-through coolant VMC's in small and medium scale manufacturing industries.

Table 1: Specifications of through coolant drill

Tool material	Coating	Drill diameter (mm)	Flute length (mm)	Point angle (⁰)
Micro grain carbide	TiAIN	10	61	140

Table 2: Specifications of the coolant

Type	Grade	PH (3% solution)	Coolant concentration
Semi synthetic coolant	Tectyl cool 260B	-9.7	3%

Design of Experiment

Taguchi method is commonly used for the design of experiment [9, 10]. In the present investigation, four process parameters were selected and their range was selected, so as to maximize the production rate. Range and levels of input process parameters are shown in Table 3. The L9 orthogonal array was selected, which consists of nine rows and four columns as shown in Table 4.

Conduction of Experiment

As per orthogonal array, experiments were conducted on the HPC experimental set up. The experiments were randomized to avoid any error in the results. The HPC jets developed through the drill tool is shown in Figure 2 and the HPC drilling operation in workpiece is shown in Figure 3.

Table 3: Range and levels of input process parameters

Process parameter	Minimum level 1	Middle level 2	Maximum level 3
Coolant pressure	7	13.5	20
Spindle speed	1500	3000	4500
Feed rate	0.05	0.165	0.28
Peck depth	10	15	20

Table 4: Orthogonal array

Expt. No.	Coolant pressure (bar)	Spindle speed (rpm)	Feed rate (mm/rev)	Peck depth (mm)
1	7	1500	0.05	10
2	7	3000	0.165	15
3	7	4500	0.28	20
4	13.5	1500	0.165	20
5	13.5	3000	0.28	10
6	13.5	4500	0.05	15
7	20	1500	0.28	15
8	20	3000	0.05	20
9	20	4500	0.165	10

Figure 2: HPC jets through the drill tool

Figure 3: HPC drilling

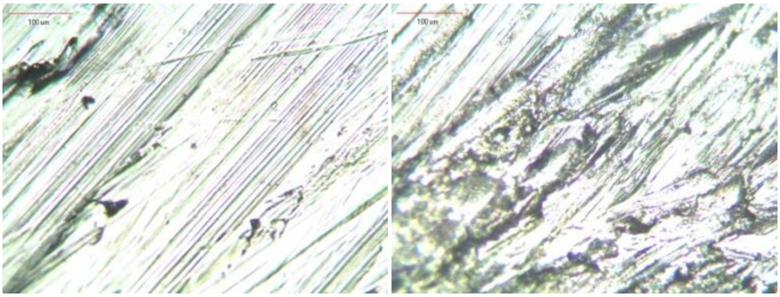
Experimental Results

Surface roughness of drilled hole was measured with Mitutoyo surface roughness tester as shown in Figure 4. From top and bottom surface of workpiece, roughness was measured at a position of 6 mm and the measured value was represented as surface roughness at top and surface roughness at bottom, respectively. The average values of hole surface roughness are given in Table 5. Figure 5(a, c, e) and Figure 5(b, d, f) show the micrographs of the hole surface at the top and bottom position, respectively at the magnification of x10 (100 µm).

Figure 4: Set up for surface roughness measurement

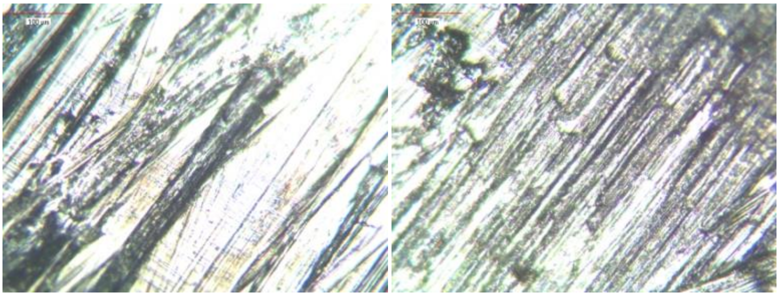
Table 5: Experimental results

Expt. No.	Hole surface roughness at top (µm)	Hole surface roughness at bottom (µm)
1	1.35	2.63
2	1.30	2.44
3	0.83	1.02
4	0.72	0.95
5	0.39	0.61
6	0.17	0.25
7	0.83	0.86
8	0.29	0.52
9	0.25	0.51



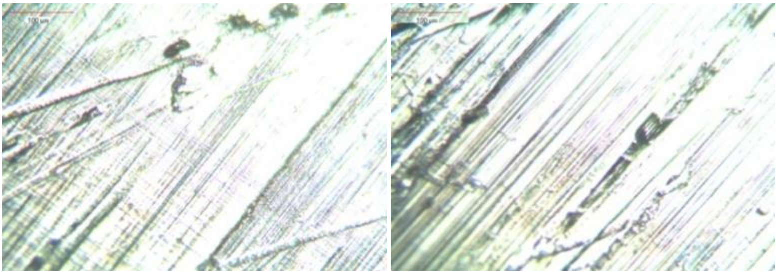
(a) (b)

Experiment No. 3: coolant pressure: 7 bar; spindle speed: 4500 rpm; feed rate: 0.28 mm/rev; peck depth: 20 mm



(c) (d)

Experiment No. 5: coolant pressure: 13.5 bar; spindle speed: 3000 rpm; feed rate: 0.28 mm/rev; peck depth: 10 mm



(e) (f)

Experiment No. 9: coolant pressure: 20 bar; spindle speed: 4500 rpm; feed rate: 0.165 mm/rev; peck depth: 10 mm

Figure 5: Micrograph of hole surface at top and bottom.

Analysis of Results

The experimental design, plots and analysis have been carried out using Minitab 17 software. "Smaller is better" criterion was used for the determination of S/N ratios, as smaller values of surface roughness are necessary for better drilling performance. The S/N ratio of output characteristics for each input parameter was calculated from the experimental results and main effects of process parameters for S/N data and mean data were plotted.

Analysis of hole surface roughness at top

Response table and main effects plot for signal to noise ratios is shown in Table 6 and Figure 6, respectively. Response table and main effects plot for means is shown in Table 7 and Figure 7, respectively.

Table 6: Response table for signal to noise ratios

Parameter level	Coolant pressure (bar)	Spindle speed (rpm)	Feed rate (mm/rev)	Peck depth (mm)
1	-1.0890	0.6217	7.8455	5.8711
2	8.8077	5.5506	4.2052	4.9102
3	8.1372	9.6836	3.8052	5.0746
Delta	9.8967	9.0618	4.0403	0.9609
Rank	1	2	3	4

Table 7: Response table for means

Parameter level	Coolant pressure (bar)	Spindle speed (rpm)	Feed rate (mm/rev)	Peck depth (mm)
1	1.1600	0.9667	0.6033	0.6633
2	0.4267	0.6600	0.7567	0.7667
3	0.4567	0.4167	0.6833	0.6133
Delta	0.7333	0.5500	0.1533	0.1533
Rank	1	2	3.5	3.5

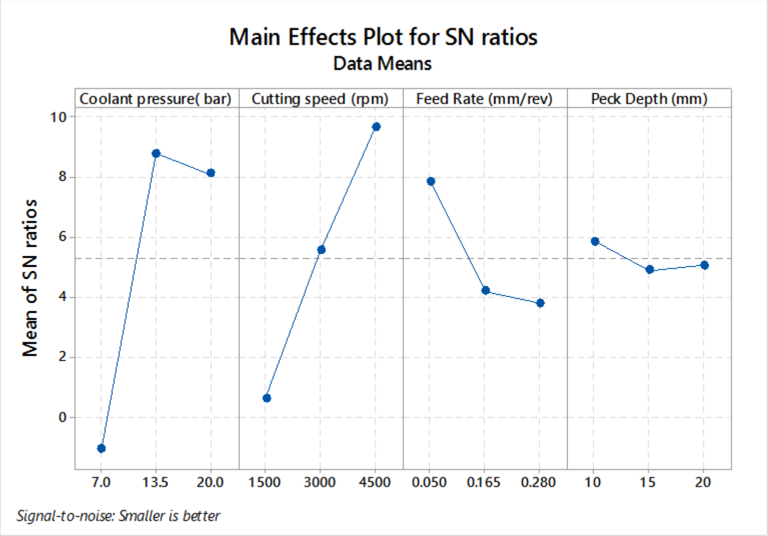


Figure 6: Main effects plot for S/N ratios

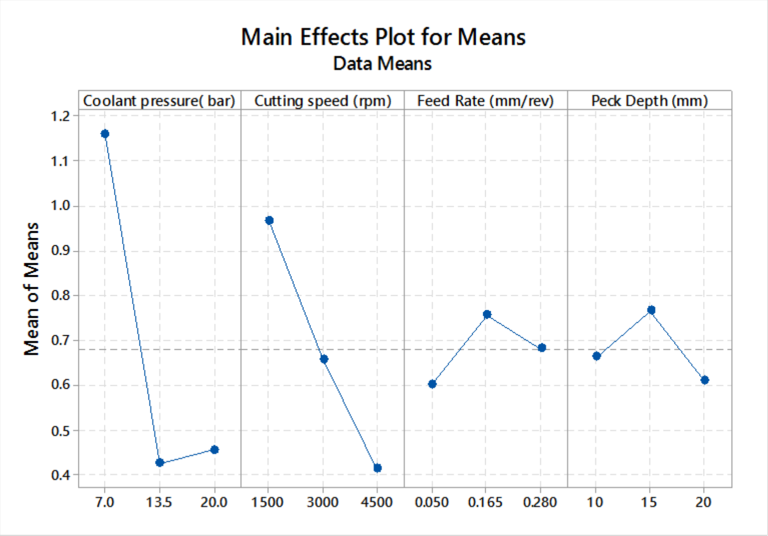


Figure 7: Main effects plot for means

Analysis of hole surface roughness at bottom

Response table and main effects plot for signal to noise ratios is shown in Table 8 and Figure 8, respectively. Response table and main effects plot for means is shown in Table 9 and Figure 9, respectively.

Table 8: Response table for signal to noise ratios

Parameter level	Coolant pressure (bar)	Spindle speed (rpm)	Feed rate (mm/rev)	Peck depth (mm)
1	-5.4396	-2.2145	3.1185	0.5810
2	5.5934	0.7530	-0.4846	1.8678
3	4.2907	5.9059	1.8105	1.9956
Delta	11.0330	8.1204	3.6031	1.4147
Rank	1	2	3	4

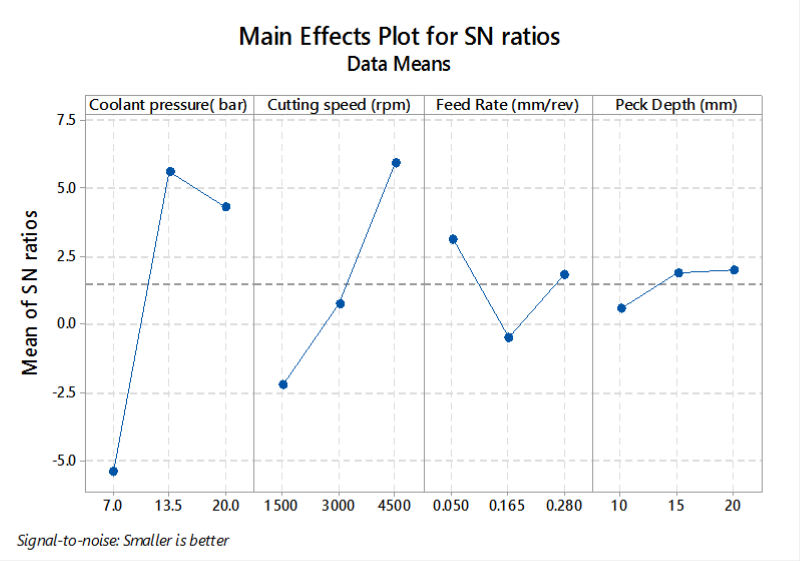


Figure 8: Main effects plot for S/N ratios

Table 9: Response table for means

Parameter level	Coolant pressure (bar)	Spindle speed (rpm)	Feed rate (mm/rev)	Peck depth (mm)
1	2.0300	1.4800	1.1327	1.2500
2	0.6033	1.1893	1.3000	1.1833
3	0.6293	0.5933	0.8300	0.8293
Delta	1.4267	0.8867	0.4700	0.4207
Rank	1	2	3	4

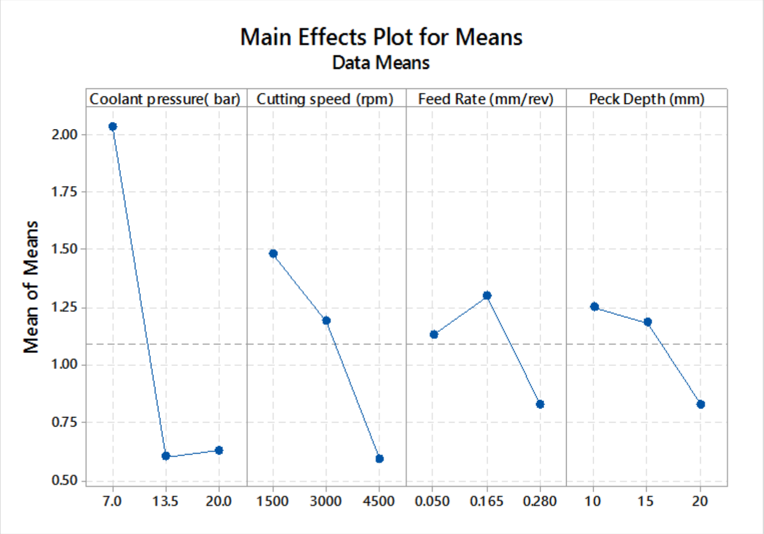


Figure 9: Main effects plot for means

Discussions

Effects of process parameters

The effects of input parameters on the surface roughness of hole were analyzed with the help of main effects plot for means as shown in Figure 7 and Figure 9.

Effect of coolant pressure

Surface roughness at top and bottom of hole decrease, as coolant pressure increase from 7 bar to 13.5 bar. This indicates that, higher coolant pressure results in improved cooling and chip removal abilities of the coolant. But surface roughness at top and bottom increase with very small rate, as coolant pressure increase from 13.5 bar to 20 bar. Thus, coolant of 13.5 bars optimal pressure [5, 19] was sufficient to achieve the better surface roughness.

From mean values of surface roughness given in the column of coolant pressure of Table 7 and Table 9, surface roughness at top is lower than that the bottom, at all levels of coolant pressure. At level 1 of coolant pressure, surface roughness at top was 87% lower as compared to the surface roughness at bottom. At level 3 of coolant pressure, surface roughness at top was 17% lower as compared to the surface roughness at bottom. Thus, as coolant pressure increases, difference between surface roughness at top and bottom decreases. Therefore, higher coolant pressure considerably reduces the surface roughness at bottom of hole.

Effect of spindle speed

Surface roughness at top and bottom of hole decrease with increase in spindle speed. As spindle speed increase, cutting time is reduced, which results in reduced thrust force, reduced workpiece distortion and hence, surface finish is improved [20]. From mean values of surface roughness given in the column of cutting speed of Table 7 and Table 9, surface roughness at top of hole was decreasing at comparatively faster rate than the surface roughness at bottom, when spindle speed was increased. At level 1 of cutting speed, surface roughness at top was 51% lower as compared to the surface roughness at bottom. At level 3, surface roughness at top was 17% lower as compared to the bottom of hole. Therefore, higher cutting speed considerably reduces the surface roughness at bottom of hole.

Effect of feed rate

It is seen that, surface roughness at top and bottom of hole increases with increase in feed rate from 0.05 mm/rev to 0.165 mm /rev. This was due to the fact that, as feed rate increase, thrust force also increase. However, it is seen that surface roughness at top and bottom decreases, when feed rate increases from 0.165 mm/rev to 0.28 mm/rev. This may be due to the fact that, high coolant pressure and spindle speed control the increase in the surface roughness due to high feed rate.

From mean values of surface roughness given in the column of feed rate of Table 7 and Table 9, at level 1 of feed rate, surface roughness at top was 53% lower as compared to the surface roughness at bottom. At level 3 of feed rate, surface roughness at top was 15% lower as compared to the surface roughness at bottom.

Effect of peck depth

It was observed that, surface roughness at top and bottom decreases with increase in peck depth. When peck depth increases, number of engagements and retractions of drill tool decreases, which results in reduced impact stresses and hence, surface roughness decreases. It indicates that, use of higher coolant pressure in drilling allow higher peck depth for lower surface roughness, which can reduce the cycle time and production cost.

From mean values of surface roughness shown in the peck depth column of Table 7 and Table 9 at level 1, surface roughness at top was 59% lower as compared to the surface roughness at bottom. At level 3, surface roughness at top was 21% lower as compared to the surface roughness at bottom.

Comparative effects

Based on the discussion of effects of process parameters on the surface roughness and Table 5, it is concluded that the surface roughness at the bottom was considerably higher than the top, which is also supported by the micrographs of the hole surface shown in Figure 5. The micrographs show that, hole surface at the bottom has more feed mark, chip marks, smearing and distorted area than the surface at top. This was due the fact that, higher temperature, vibrations and chip accumulation at the bottom of hole results in more distortion of the drilled hole surface. Also from Table 5, in few cases surface roughness values obtained with HPC drilling were considerably low and competitive with finishing operations.

Significant parameters

From the delta values of surface roughness and ranks shown in Table 7 and Table 9 of response table for means, significant factors affecting on the surface roughness were determined. It was observed that, coolant pressure followed by spindle speed was significant input parameters for the surface roughness at the top and bottom of hole.

Optimal level of process parameters

Main effects plot for S/N ratios were used to obtain the most favorable values of process parameters [21]. The level of a parameter with highest signal to noise ratio provide the optimal level [22]. Thus from Figure 7 and Figure 9, optimal levels of parameters for HPC drilling at the top and bottom of hole are shown in Table 10. It is seen that, optimal value of peck depth was different at the top and bottom of hole, which is not possible from the production point of view. Therefore, practically feasible optimal level of process parameters for the undertaken HPC drilling process is also shown in Table 10.

Table 10: Optimal level of process parameters

Process parameter	Optimal value		
	At top	At bottom	Feasible
Coolant pressure (bar)	13.5	13.5	13.5
Spindle speed (rpm)	4500	4500	4500
Feed rate (mm/rev)	0.05	0.05	0.05
Peck depth(mm)	10	20	20

Verification of Results

The confirmation experiments were carried at optimal level of process parameters at the top and bottom of hole and average experimental value of hole surface roughness at the top and bottom was measured to be 0.17 µm and 0.22 µm respectively. The percentage error in the surface roughness at the top and bottom of hole has been found to be 5% and 6.5%, which was acceptable [23] and hence experimental results were verified.

Conclusions

Based on analysis and discussion of HPC drilling process, following conclusions were drawn.

- Optimal coolant pressure of 13.5 bar pressure was sufficient to achieve the better surface roughness.
- Surface roughness at the top of hole was considerably lower than the bottom of hole under the action of process parameters.
- Surface roughness values obtained with HPC drilling process were low and even in few cases; surface roughness was competitive with the finishing operation such as grinding operation.
- Supply of coolant at high pressure in drilling has permitted large peck depth for smaller surface roughness value; which indicates that the manufacturing cost can be reduced with HPC drilling process.
- Optimal value of process parameters in HPC drilling were investigated as; coolant pressure: 13.5 bar, spindle speed: 4500 rpm, feed rate: 0.05 mm/rev and peck depth: 20 mm.
- Coolant pressure and spindle speed were observed to be the significant process parameters affecting on the hole surface roughness in HPC drilling process.
- As a continuation of research process, the study should be undertaken to determine interactive effects of coolant pressure, spindle speed, feed rate and peck depth on the responses in HPC drilling process. Effect of tool geometry, difficult to machine materials and higher length to diameter aspect ratio may also be investigated in HPC drilling. The thermal aspects

of coolant, tool and chip during deep hole drilling must be investigated to explore the insights of HPC drilling process.

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