RESEARCH ARTICLE

INTERNATIONAL RESEARCH JOURNAL OF MULTIDISCIPLINARY TECHNOVATION

Asian Research Association

DOI: 10.54392/irjmt25315

Deep Hole Drilling of AISI 316 Steel using CNC Peck Drilling Approach and Parametric Study

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DOI: https://doi.org/10.54392/irjmt25315

Received: 08-12-2024; Revised: 17-04-2025; Accepted: 04-05-2025; Published: 10-05-2025

Abstract: Drilling is a crucial machining process in manufacturing, often used for assembly purposes. Assembly challenges develop as a result of inappropriate hole geometry, such as circularity, perpendicularity and cylindricity regardless of whether the tolerance is within the limit. Deep hole drilling is a specialized technique to create holes with high depth to diameter ratio. In various industries, such as oil and gas, shipbuilding, and aerospace, deep hole drilling of stainless steel is performed to make components like drill collars, rotor shafts and fuel injector nozzles. This study investigates the impact of drilling process parameters on the hole quality, using Taguchi design of experiments for AISI 316 drilling optimization. Deep hole drilling experiments were carried out based on a Taguchi L9 array, with 3 different drills (HSS, M35, TiAlN); at 3 different cutting speeds and feed rates. The innovative concept of intermittent drilling and retraction is applied using CNC vertical milling machine and the results are examined for the achievable tolerance on size and geometry. Results indicate that the cutting tool material is the most significant factor influencing roundness, cylindricity, and hole size, followed by feed and speed. Speed has a lesser effect on perpendicularity compared to the cutting tool type and feed. Feed exerts a greater influence on surface roughness than the cutting tool type. Chip morphology indicates HSS drillbit is effective and stable in the process of producing quality holes.

Keywords: Deep Hole Drilling, Circularity, Cylindricity, Perpendicularity, AISI 316, Taguchi

1. Introduction

Drilling is a vital process in the manufacturing sector which involves removing a cylindrical volume of material from a solid block, thereby creating a hole. It is extensively used in the aerospace sector, automobile, airplane, and many more industries as an assembly operation. Successful drilling of stainless steel depends on choosing the right drill bits. They have to be strong enough to withstand wear resistance and serve for long period of time. Once started drilling, the stainless steel work piece will quickly run into work hardening, because of its ductility and low thermal conductivity [1]. This will increase the wear and tear of drill bits and the time it takes to complete drilling a hole. The best way to manage work hardening is through patience and skill. While drilling, the tool should be kept cool and well lubricated. Drill bits with coatings maintain their sharp cutting edge and have higher tool life than the drills uncoated [2]. Nevertheless, drill bit flute geometry is the most significant factor influencing hole quality and chip evacuation from drilling zone [3]. Drilling performance of stainless steel has been investigated for hole quality ehancement using different tools such as High Speed Steel (HSS), M35HSS, M42HSS (molybdenum series), Titanium Nitride coated and Titanium Aluminium Nitride (TiAlN) coated Carbide/HSS tools [4-6]. Figure 1(a) shows a visualization of the two motions of twist drill, feed in vertical direction and rotation about the drill axis. D.Biermann et al. mentioned that a deep hole is characterized by its depth-to-diameter ratio (D:d), and holes with larger than 10:1 ratio are usually called deep holes [7]. Deep hole drilling differs from regular drilling in that, a substantial amount of cooling lubricant must be fed to the cutting blades at high pressure, so as to enable chip clearing from the cutting zone. Though there are special methods like Gun drilling and BTA drilling (Boring and Trepanning Association) for deep hole drilling, this study explores the possible use of CNC peck drilling approach wherein the tool is fed intermittently after repeated tool retractions, as shown in Figure 1(b). Gun drilling tool differs from a twist drill in its unique geometry having a single cutting edge and straight flutes, which helps to carry the cutting fluid into the cutting zone and remove chips out the cutting zone. Whereas the BTA drilling uses modular tool with cutting inserts and high pressure coolant for chip removal. Gun drilling is used for making small holes (less than 20mm dia). BTA drilling is used for larger diameter deep holes with specially designed drill heads and indexable cutting inserts [7, 8].

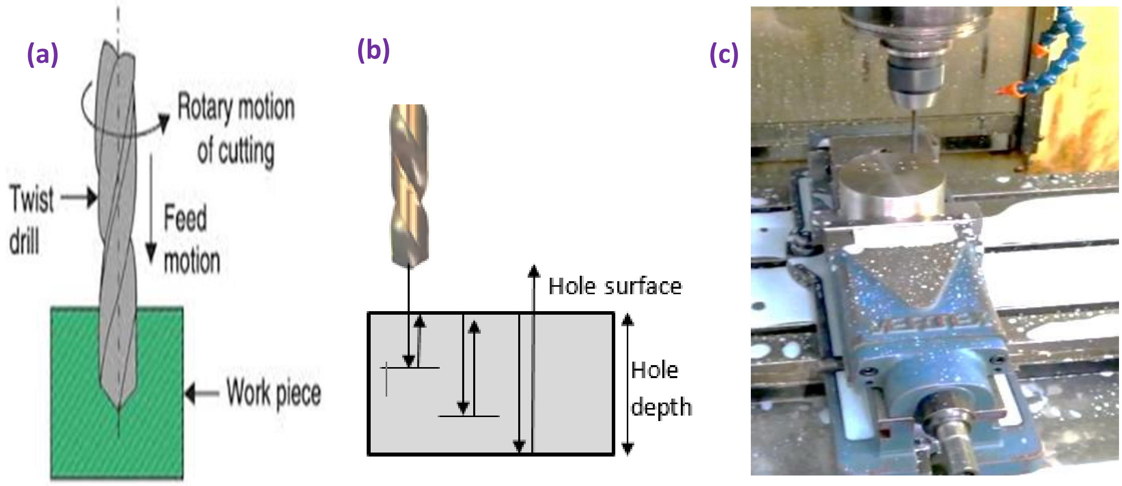


Figure 1 (a) Twist drill motions, **(b)** Schematic view of peck drilling, **(c)** Experimental setup for peck drilling

With BTA and gun drilling techniques, the machinery set up and maintenance are known to be time consuming and complex. This paper investigates the parametric study and optimization of peck drilling of AISI316 steel in CNC Vertical Milling machine using standard twist drills to produce deep holes, shown in Figure 1(c). Resulting hole quality is examined using Coordinate Measuring Machine and MINITAB16 software package for Taguchi optimization.

Taguchi technique is widely used for arriving at the best operating parameters of a process by introducing the concept of robust design, wherein the process is not affected by uncontrollable factors. The objective in robust design is to minimize sensitivity of a control factor to noise factors, such as temperature or work material property variations, etc. Using Taguchi technique, we can identify those control factors that reduce variability in the process output through the S/N ratio study. The S/N ratio is a measure that compares the level of a desired signal to that of background noise. Under regular drilling conditions several authors have demonstrated the use of Taguchi method optimization [9, 10]. Drilling parameter optimization through desirability function was researched by Ramachandran et al. using analysis of variance and linear regression to determine the most significant control factors affecting the surface roughness in drilling stainless steel [11]. The influence of machining parameters (spindle speed, feed, and depth of cut) are investigated in detail, taking into account good surface finish, and then various parametric optimization algorithms are applied to improve the machining processes. It is found that the chip evacuation behaviour of the drilling tool plays a significant role. Khushboo Sharma et al, performed an experimental investigation to optimize the machining parameters of aliminium AA6082. Feed rate, speed, presence or absence of cutting fluid and hole depth are taken into consideration to maximize the material removal rate and surface roughness [12]. Sundar Singh Sivam et al, identified optimal drilling conditions for AM60 magnesium alloy. The results of drilling AM60 magnesium alloy are optimized using the ANOVA technique. The effect of speed, feed, drilling time and drill bit treatment was investigated considering the response factors like residual stress, thermal stress, surface roughness, vibration, concentricity, cylindricity and perpendicularity [13]. Tarakeswar Barik et al found that machine parameter settings and drill point angle have a substantial impact on hole quality after their experiments on drilling CFRPs [14]. Optimized set of input parameters were identified by Alagappan KM et al, for drilling hybrid FRP using WC coated HSS drills, which are as follows: Feed Rate: 450 mm/min, Cutting Speed: 3,000 rpm, and Drill Diameter: 5mm [15]. C Sarala Rubi et al, investigated the effect of process variables including reinforcement, drill type, speed, and feed rate on thrust force and burr height in drilling Aluminium matrix composite [16].

Deep hole drilling typically serves the following domains in its respective applications: aerospace and defence, automotive applications, oil and gas exploration. Tool settings and factors should be carefully determined to improve product quality. Circularity, cylindricity and perpendicularity are the most sought-after geometrical properties of precision machined components in the industry and quite a good extent of research is directed towards obtaining the desired limits of such geometrical parameters through machining processes optimization [17, 18]. Arshad Noor Siddiquee et al focused on optimizing deep drilling parameters based on Taguchi method for minimizing surface roughness. Experiments were conducted on CNC lathe machine using solid carbide cutting tool on AISI 321 austenitic stainless steel [19]. Esmaeil Damavandi et al, performed optimization of the deep drilling process using the Taguchi method on three materials with three distinct cutting tools in order to investigate their effect on power, tool wear and surface roughness [20]. Drilling thrust and torque in the deep hole drilling process are found to continuously increase with the drilling depth, leading to drill breakage when drilling forces are greater than the allowable limit [21]. To reduce the cost and complexity of machining of deep holes, often performed on specialized drilling machines, the peck drilling of deep holes is investigated using a CNC vertical milling machine. This research further delves into the optimization of deep hole drilling of AISI 316 stainless steel and observation of the attainable range of hole size accuracy and geometrical tolerances.

2. Materials and Methods

2.1 Workpiece and Cutting tools

Deep hole drilling experiments are conducted on AISI 316 stainless steel block of diameter 100mm and thickness 50mm. Stainless steel 316 is generally composed of 16 – 18% chromium, 10 – 14% nickel, 2 – 3% molybdenum, and about 0.08% carbon. Stainless steel is harder to machine and requires special tools for cutting. It's prone to work hardening from overheating during drilling. To avoid overheating, the use of oil for lubrication is preferred. The quality of work can be improved by altering machining conditions such as coolant type, cutting tool type, cutting tool radius, tool material type, and working material hardness. Effect of drilling on hole quality, using three different drilling tools is considered in this study, namely, High-Speed Steel (HSS) Drills, M35 HSS Cobalt Drills and Titanium Aluminium Nitride (TiAlN)-Coated Drills. The nominal diameter of each tool is 5 mm and the flute length is 52 mm. HSS is a type of tool steel containing high amounts of carbon and other alloying elements such as tungsten, chromium and vanadium (18:4:1 ratio) with small amounts of molybdenum. M35 is a type of HSS drill with added cobalt content, which increases its heat resistance and hardness compared to standard HSS. TiAlN is a coating applied to drills made from various materials including HSS and solid carbide.

2.2 CNC Milling Machinne

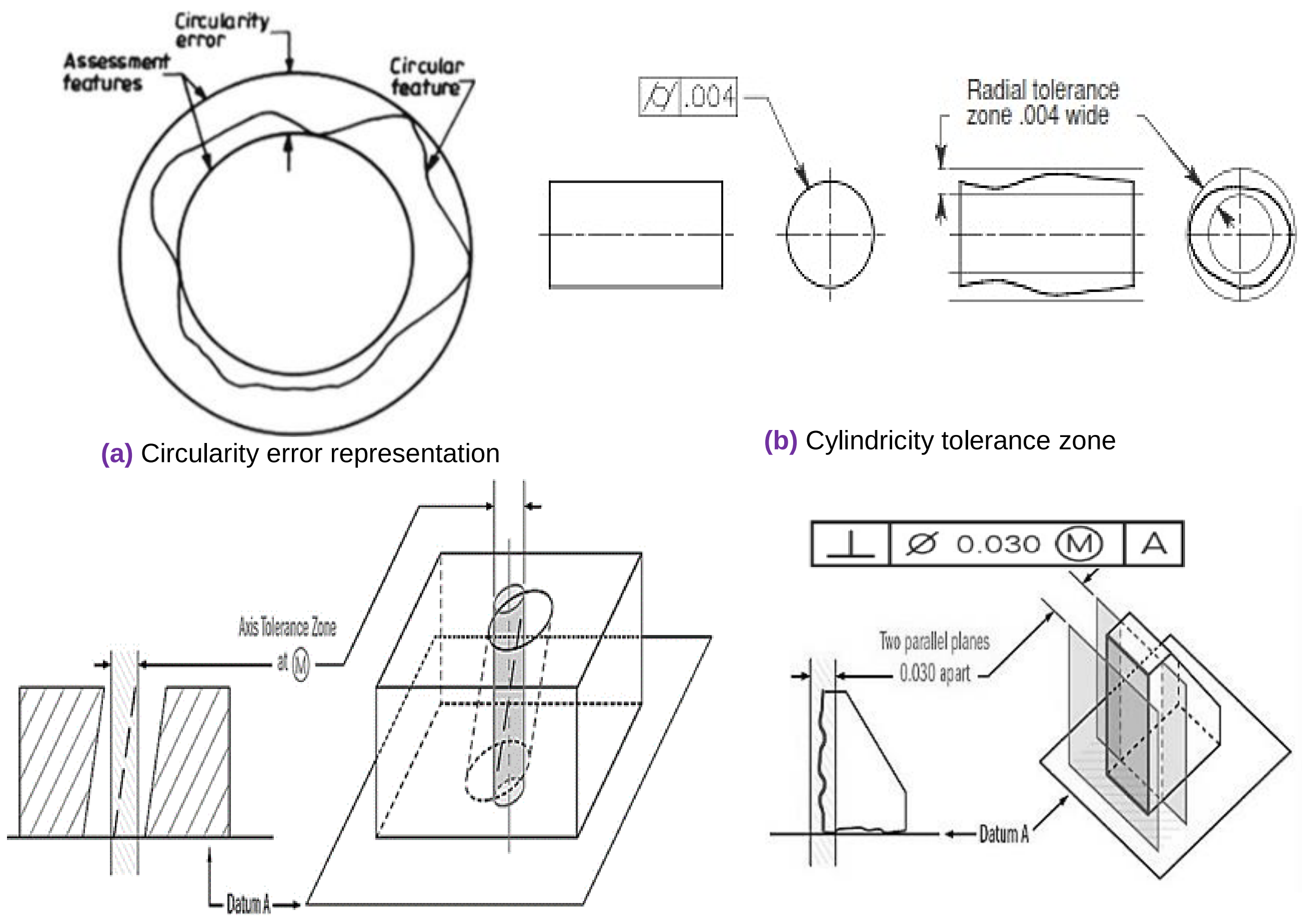
Deep hole drilling of stainless steel is performed on a vertical CNC milling machine using the peck drilling technique. Peck drilling is a method for improving chip removal and coolant delivery during deep hole drilling operations. Retracting the drill bit on a frequent basis breaks up and evacuates chips from the hole, reducing the possibility of chip blockage and heat accumulation. Deep hole drilling is often done with special equipment, however in this case, it is attempted with a regular CNC milling machine to save manufacturing costs and can also be utilized when special equipment is not accessible for machining.

A conventional CNC mill has three axes, X, Y and Z. The spindle symbolizes the Z-axis, which moves upward and downward of drilled hole. Left to right movement of the machine table is the X-axis travel, whereas Y-axis moves back and forth of the operator. CNC Milling machine that is used in the experiments is shown in Figure 1(c). G83 peck drilling cycle is employed; G83 X Y Z R P Q F, where X = Coordinate of hole (Optional), Y = Coordinate of hole (Optional), Z = Depth of hole, R = Retract value, P = Dwell time at bottom of hole, Q = Depth of each peck, F = Feed rate. The G83 peck drilling cycle retracts the tool after each peck. The variable R on the line of code controls the retracted height (Ex: G83 Z-2.0 R2.5 Q0.2 F80). For chip clearing, the drill may be retracted above the component work surface after each pecking cycle.

The machining time in CNC peck drilling is the cycle time taken by the CNC machine to execute the program for each hole. It is the total time required for deep hole drilling of a 50 mm through hole (50 mm hole depth) following the peck drilling cycle, shown in Figure 1(b). The peck drilling cycle is constituted by an incremental forward drill movement up to a peck depth of 0.2 mm followed by retraction, and the cycle is repeated upto the required depth defined in peck drilling cycle. The pecking cycle is repeated until the total depth of hole drilled reaches the required hole depth of 50 mm.

2.3 Co-ordinate Measuring Machine (CMM)

A coordinate measuring machine (CMM) made by ZEISS PRISMO vast, measures hole diameter and roundness. The instrument is linked to the measurement software CALYPSO, this is used to collect measured data for subsequent processing. For measuring circularity, also called roundness, the pointer is placed over at least 4 locations to assess roundness. The value to be measured is determined using the least-squares method that reduces the sum of variations from all measurements. The standard built-in software package of the CMM also calculates the diameter of the holes inspected. The measurement of these values is crucial in ensuring that the tolerances of the manufactured part are within the limit values. The schematic view of circularity error or roundness of a particular hole is represented in Figure 2 (a). Cylindricity tolerance is a 3D tolerance on hole size along its length, involving a tolerance range limited by two concentric cylinders, as shown in Figure 2(b), separated by 0.004 mm, for example. Cylindricity is a composite form tolerance that simultaneously controls circularity, straightness of a surface, and taper of cylindrical features [22]. For calculating cylindricity, it is necessary to measure radial form (roundness), axial form (vertical straightness), and dimensional uniformity (parallelism). In CMM, defects are positioned on the geometrically ideal cylinder; the deviations are produced and layered on the ideal cylinder; and the fitting element is calculated applying the approximation criteria. There are four fitting methods frequently used: Least Square Cylinder, Minimum Circumscribed Cylinder, Maximum Inscribed Cylinder, and Minimum Zone Cylinder [23].



(a) Circularity error representation

(b) Cylindricity tolerance zone

(c) Axis perpendicularity

(d) Surface perpendicularity

Figure 2. Circularity, Cylindricity and Perpendicularity tolerance zone [25].

Perpendicularity can refer to two different phenomena; perpendicularity on the surface and along the axes. Axis Perpendicularity tolerance limit determines how perpendicular a given axis must be, referring to a datum. The axis perpendicularity tolerance zone, as depicted in Figure 2(c), is a pair of planes that are mutually parallel and perpendicular to a reference plane, that ensures the alignment of hole axis. To determine perpendicularity error, the workpiece is aligned using a reference plane. To ensure the probe head is normal to the workpiece, it was mapped using many points on the top surface. The shifting of the hole axis from the reference plane (top plane) indicates the hole perpendicularity error [24]. Surface perpendicularity is defined using two parallel planes that serve as a tolerance zone for the surface element, shown in Figure 2(d).

2.4 Measurement of Hole Surface Roughness

Surface roughness, an essential characteristic in metal cutting, is influenced by drilling processes and affects mechanical properties like creep life, corrosion resistance, and fatigue behaviour. Drilled surface roughness is measured using a surface roughness testing method as per IS 3073:1967. Surface finish is crucial for drilled hole quality, and small roughness can affect processes and product reliability. Surface roughness is typically measured using a stylus movement device and it measures the depth-wise variations of surface profile, with greater variations indicating rough surfaces. The CMM measures average surface roughness (Ra) as the average of values measured at a minimum of five points along the direction of hole depth. Further measurements of Rz and Rq are helpful to better assess the nature of surface produced by the peck drilling operation.

2.5 Optimization Methodology

Optimization techniques are useful to improve surface quality, reduce circularity, cylindricity and diameter error in machining of steel [26, 27]. S Sheth et al, mainly focused on cylindricity and perpendicularity as output parameters in drilling process because they are important in assembly of two mating components withh holes [28]. Design of Experiments aids in planning experiments, which are then utilized for analysis and modelling of the process. The Taguchi method is a sophisticated experimental design method that uses orthogonal arrays to study total parameters and responses with limited experiments. A separate table is created for these values. Its rows and columns comprise of parameters and their values at different levels. The "orthogonal array" design explores the whole parameter range with a limited number of trials. Table 1 shows the factors controlling the drilling process and their levels in this experiment, while Taguchi L9 Orthogonal Array of experimental design is shown in Table 2. It shows the combination of control factors and their levels for conducting the nine experimental runs. The experimental data so obtained may be analyzed using Taguchi technique to determine the impact of cutting parameters. The smaller-the-better type of drilling performance criteria may be applied for response parameters including surface roughness, hole diameter deviation and geometrical tolerance parameters [29].

Table 1. Factors and Levels

FACTORS	LEVELS		
	1	2	3
Drill material (A)	HSS	M35	TiAlN
Spindle speed (rev/min) (B)	700	750	800
Feed rate (mm/rev) (C)	0.05	0.1	0.15

Table 2. Taguchi L9 Orthogonal Array

RUN	CONTROL FACTORS AND LEVELS		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Experimental results consist of the response factors (quality characteristics): roundness, cylindricity, hole diameter, perpendicularity and average surface roughness, measured at each one of the nine experimental runs as per Taguchi array of experiments. The measured values of responses are converted into "S/N" ratios to measure quality characteristics, with three levels for optimal parameter assessment. As per Taguchi's processes, the S/N ratios are summed for every level for every parameter (response factor), and their mean is calculated. A response table of the S/N ratio of each response parameter, Delta Values, Contribution Rank is obtained. The lowermost two columns display the delta valves and rankings of each parameter. Rank indicates the influence of each parameter separately. Minitab software is used for getting the response table for each response factor under different control factors and their levels.

3. Results and Discussion

Machining time obtained from CNC Machine for drilling each hole for the each set of experimental parameters is shown in Table 3. Machining time is less for drilling Hole No.3 which is 8 minutes 39 seconds using HSS tool. The values for roundness, cylindricity, diameter, perpendicularity is shown in Table 4. The data collected show that roundness is less for hole numbers 6 and 7. The lowest roundness value was obtained using M35 tool at 800 rpm and a feed rate of 0.05mm/rev, and using TiAlN tool at 700rpm and a feed rate of 0.15mm/rev. Cylindricity is minimum for holes 6, 5, and 4 machined by M35 drill bit. Hole 4 drilled with M35 drill at 700 rpm and 0.1 mm/rev has resulted in a smallest hole size error (i.e) diameter of 5.5593 mm.

In these experiments, M35 and HSS tools in general have undergone wear resulting in diameter deviation of 5.56 to 5.60mm, compared to TiAlN drills which produced diameter of 5.76 to 5.87 mm. Hole diameter variations may not be fully attributed to roundness or cylindricity errors, indicating possible elastic recovery of workpiece apart from possible tool wear. Larger diameter deviation with TiAlN tool indicates the extent of wear and loss of cutting ability. Hole 2 has the smallest perpendicularity angle. Variation in perpendicularity in not significant for various drill tool materials at various speeds and feeds. Due to their higher coefficient of friction, inferior adhesion compared to other coatings, and tendency to generate heat during the drilling process, TiAlN-coated drills may not consistently produce high-quality holes in stainless steel. Brittleness of TiAlN coating affects the drill performance under jerk or impact loading, notable in the pecking process. It suffers from adhesive wear on the wear pad and chemical diffusive wear on the flank face in addition sliding wear and chipping. The heat generated by the drilling process can lead to thermal expansion of the drill and workpiece which could affect the size and quality of the drilled holes leading to oversized holes [30, 31].

The graphs for circularity, cylindricity, hole diameter and perpendicularity vs hole number are shown in Figure 3(a-d) respectively. The data collected show that roundness is less for hole numbers 6 and 7. The lowest roundness value was found using M35 tool at 800 rpm and a feed rate of 0.05mm/rev, and using TiAlN tool at 700rpm and a feed rate of 0.15mm/rev. Cylindricity is within a minimum of 0.02 mm for holes 6, 5, and 4 machined by M35 drill bit and it is within 0.04 mm for holes machined with HSS drills. TiAlN drill did not performed well regarding cylindricity, which is in the range of 0.066 to 0.131 mm.

Hole 4 drilled with M35 drill at 700 rpm and 0.1 mm/rev has resulted in a smallest hole diameter of 5.56 mm. Reason could be probable drill wear. In these experiments, M35 and HSS tools in general have undergone excessive wear compared to TiAlN drills which produced hole diameter of 5.76 to 5.87 mm.

Table 3. Machining Time for drilling holes

Hole No.	Tool	Speed (rpm)	Feed (mm/rev)	Depth of cut (mm)	Machining Time (Minutes)
1	HSS	700	0.05	0.2	17min 4s
2	HSS	750	0.1	0.2	9min 41s
3	HSS	800	0.15	0.2	8min 39s
4	M35	700	0.1	0.2	10min 29s
5	M35	750	0.15	0.2	8min 45s
6	M35	800	0.05	0.2	13min 46s
7	TiAlN	700	0.15	0.2	9min 18s
8	TiAlN	750	0.05	0.2	25min 45s
9	TiAlN	800	0.1	0.2	9min 36s

Table 4. Roundness, Cylindricity, Diameter, Perpendicularity values of holes

Hole no.	Roundness (mm)	Cylindricity (mm)	Diameter (mm)	Perpendicularity (mm)
1	0.0142	0.0362	5.5931	0.3628
2	0.0058	0.0326	5.6040	0.3341
3	0.0138	0.0239	5.6018	0.4164
4	0.0146	0.0194	5.5593	0.3865
5	0.0122	0.0193	5.5605	0.3874
6	0.0099	0.0192	5.5649	0.3822
7	0.0099	0.0956	5.8735	0.3769
8	0.0149	0.0664	5.8340	0.4217
9	0.0261	0.1310	5.7580	0.3947

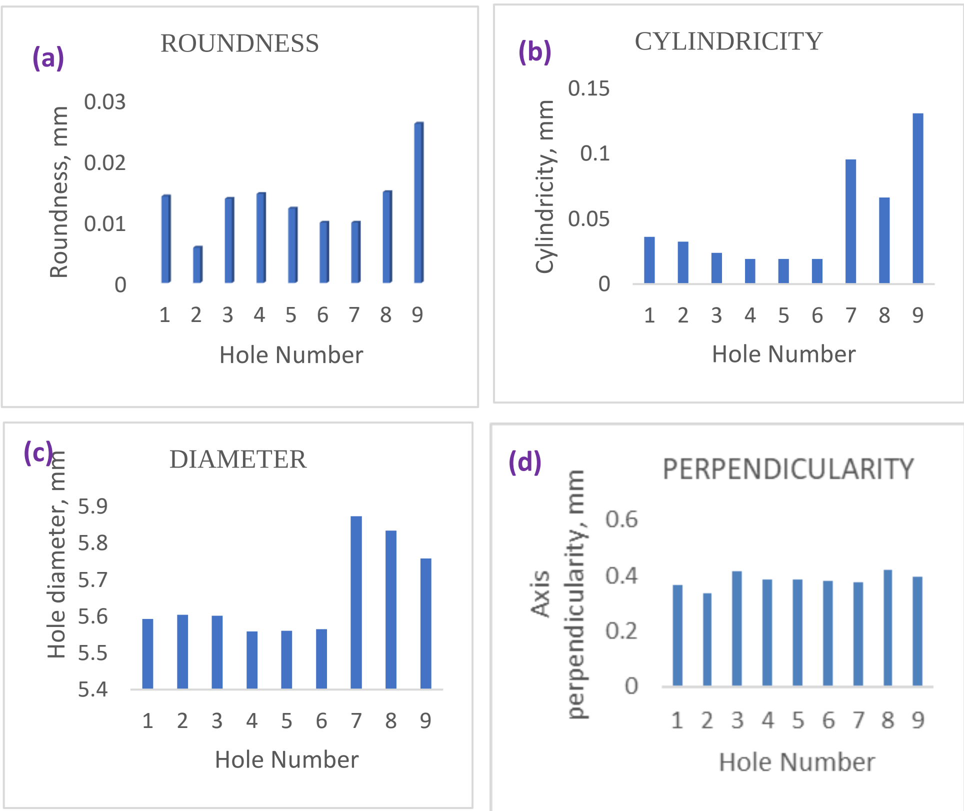


Figure 3: (a) Roundness, **(b)** Cylindricity, **(c)** Hole Diameter and **(d)** Perpendicularity measured for various tools, speed and feed rates (according to Hole Numbers in Table 3).

Table 5. Surface Roughness values for drilled holes

Hole no.	1	2	3	4	5	6	7	8	9
Ra (μm)	1.004	1.366	1.029	1.721	1.164	1.528	1.461	1.095	1.984
Rq (μm)	1.239	1.663	1.241	2.155	1.534	1.929	1.815	1.317	2.548
Rz (μm)	4.977	7.290	4.768	8.813	7.096	7.802	7.324	5.341	10.880

Looking at Figure 3 (a-c), hole diameter variations may not be fully attributed to roundness or cylindricity errors; the effect of elastic recovery of workpiece apart from tool wear are to be investigated. Hole 2 has the smallest perpendicularity error. Variation in perpendicularity is not significant for various drill tool materials at various speeds and feeds. The relatively larger values of cylindricity and hole diameter measurements after drilling with TiAlN drill shows its limitation in the peck drilling process due to loss of coating effectiveness due to wear as mentioned earlier.

The implications of the spindle speed and rate of feed on hole surface roughness is demonstrated in Table 5. Surface Roughness Measurements Ra and Rq are lower for hole number 1, and Rz is lower for hole number 3. Ra, popular in machining, is the arithmetic average of the profile height deviations from the center line over a sampling length. Rq is the root mean square of the profile deviations over the sampling length. Rz is the average of 5 largest differences of peaks and valleys within the sampling length. It is observed that roughness value Ra ranges from 1.004 μm and 1.984 μm. The rate of feed has mixed effect on roughness, while high spindle speed is suggested to reduce roughness [6]. These findings suggest that moderate values of spindle speeds and feed rate can be securely chosen to obtain smooth hole finish on the surface.

3.1 Chip Morphology

Chip shape is important to understand the favourable conditions for smoothness of a drilling process. The drilling process will be smooth if chips are well broken. The drilling chip varies in size and shape due to the change in work and tool materials, process parameters, and drill geometry. The chip formation type affects the tool wear; the fluctuating vibration components can effectively describe the chip formation type.

However, most ductile materials such as austenitic stainless steels do not break during drilling, and instead, form continuous chips. Figure 4 (a,b) show the chip morphology obtained while drilling with M35 HSS at low feed rate producing long chips while Fig.4 (c,d) show the chips obtained while drilling with same tool at high feed rate producing short length chips. Fig. 4 (e,f) show the kind of chips obtained while drilling with TiAlN coated drill at low feed rate, producing short curly chips. Compared to HSS drill bit, the short and powdered chips produced by TiAlN drill bit indicate the unstable chip formation mechanism, though it may be easily evacuated out of the cutting zone using coolant flow. Whereas the observation of long curly chips in drilling with HSS shows stable cutting and they do not show any tendency to clog within the drill flutes [32].

The graphs presented in Figure. 3 enable us to evaluate the quality of holes produced by different materials, highlighting that no single tool can achieve all desired attributes. Therefore, to attain optimal results, the tool selection process should be guided by the specific parameters. Cutting parameters significantly influence tool wear and life. The heat generated during chip removal, evident in the chip morphology, indicates substantial wear on the HSS drill, due to long curly chips produced. TiAlN drill exhibits less wear than the HSS and M35 drill. Tool wear and tool life are inversely correlated; as wear increases, tool life decreases, and vice versa. It has been shown that for lower cutting speeds, the tool wear is lesser and accordingly diameter error and roundness error are lesser [33, 34]. For an HSS, the chip is thick and continuous, while for an M35 drill, it is thin and continuous, indicating ductile mode of machining. For TiAlN drill, chips are fractured and short. Referring to the appropriate hole numbers in Tables 4 and 5, the HSS drill produces better hole quality. Consequently, the shape of the chips significantly reveals insights to the hole quality in drilling. Peck drilling enhances the removal of chips and the dissipation of heat from holes by retracting the tool to a safe height with each pass, allowing coolant to effectively reach bottom of the hole.

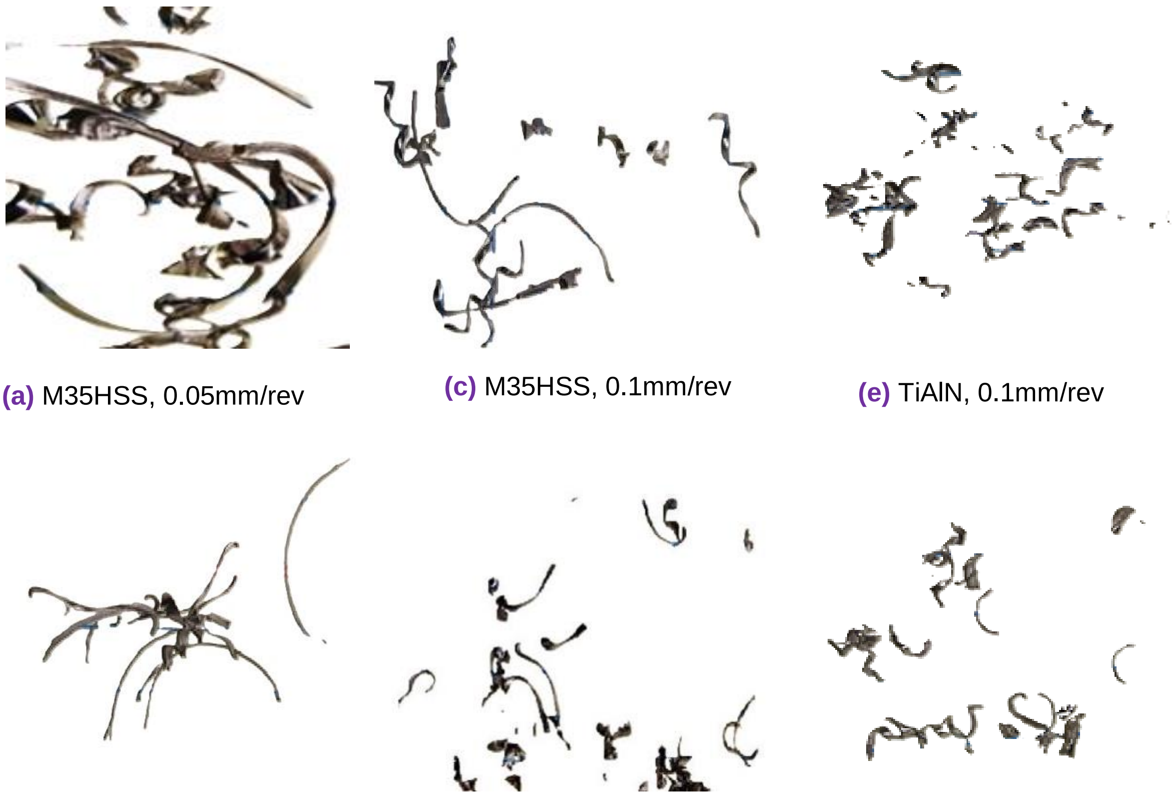
3.2 Taguchi Analysis

There are three types of S/N ratios in optimization problems. They are: Smaller is better, Larger the better and Nominal the better. As we look for keeping the response variable namely roundness, roughness, cylindricity, perpendicularity, diameter variation to the minimum, we choose 'Smaller the better' characteristic.

Accordingly, S/N ratio = -10 Log_{10} [mean of sum of squares of measured data]

This expression for S/N ratio is used for all undesirable characteristics, which are to be reduced, like "defects " for which the ideal value is zero. The generic form of S/N ratio then becomes,

S/N = -10 Log_{10} [mean of sum of squares of {measured - ideal}]



(a) M35HSS, 0.05mm/rev (c) M35HSS, 0.1mm/rev (e) TiAlN, 0.1mm/rev

(b) M35HSS, 0.05mm/rev (d) M35HSS, 0.1mm/rev (f) TiAlN, 0.1mm/rev

Figure 4 (a-d) Chips obtained at various feed rates on drilling with M35 HSS tool **(e-f)** Chips obtained on drilling with TiAlN coated tool

In this study, it is proposed to optimize three drilling parameters (tool material, speed and feed rate) using Taguchi experimental design method. Tables 6, 7, 8, 9, 10 show the S/N ratio computation for the response variables namely roundness, cylindricity, diameter, perpendicularity and roughness respectively. Each table listed above also indicates the order in which the type of tool, drilling speed and feed influences each of one the response variable.

Table 6. S/N Ratios for Roundness (Smaller is better)

Level	TOOL	SPEED	FEED
1	39.63	37.92	37.86
2	38.36	39.85	37.70
3	36.10	36.32	38.52
Delta	3.53	3.53	0.82
Rank	1	2	3

In general, the type of cutting tool is the most influential parameter with rank 1 for cylindricity, hole diameter and axial perpendicularity, followed by feed and speed in that order. Regarding roundness, type of tool followed by speed is more influential than feed. For surface roughness, feed is more influential followed by type of tool and then speed respectively.

Table 7. S/N Ratios for Cylindricity (Smaller is better)

Level	TOOL	SPEED	FEED
1	30.33	27.82	28.91
2	34.29	29.19	27.21
3	20.53	28.14	29.04
Delta	13.75	1.37	1.83
Rank	1	3	2

Table 8. S/N Ratios for Diameter (Smaller is better)

Level	TOOL	SPEED	FEED
1	-14.96	-15.08	-15.06
2	-14.90	-15.06	-15.03
3	-15.30	-15.03	-15.08
Delta	0.40	0.05	0.06
Rank	1	3	2

Table 9. S/N Ratios for perpendicularity (Smaller is better)

Level	TOOL	SPEED	FEED
1	8.646	8.513	8.220
2	8.283	8.420	8.618
3	8.017	8.013	8.107
Delta	0.630	0.500	0.511
Rank	1	3	2

Table 10. S/N Ratios for surface roughness, Ra (Smaller is better)

Level	TOOL	SPEED	FEED
1	-0.9973	-2.6811	-1.5018
2	-3.2390	-1.6055	-4.4585
3	-3.3440	-3.2939	-1.6201
Delta	2.3467	1.6884	2.9567
Rank	2	3	1

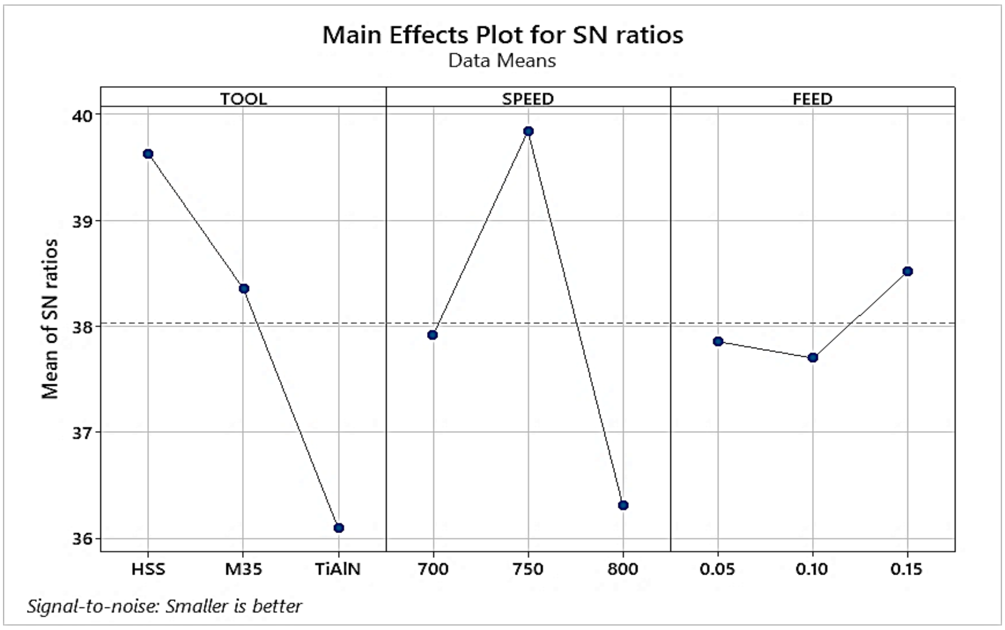


Figure 5. Main effects plot for S/N ratio of roundness

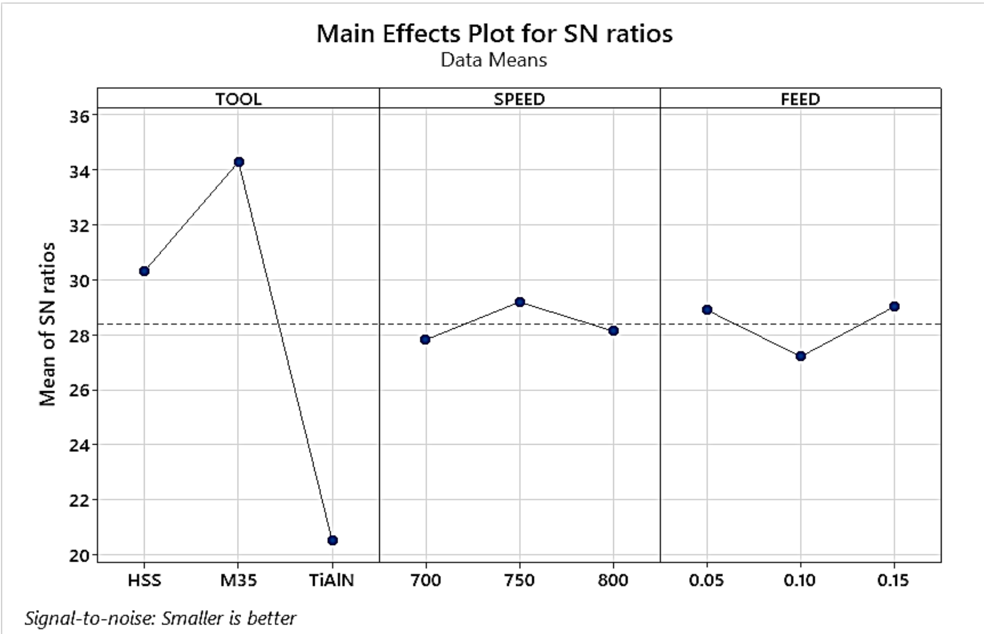


Figure 6. Main effects plot for S/N ratio of cylindricity

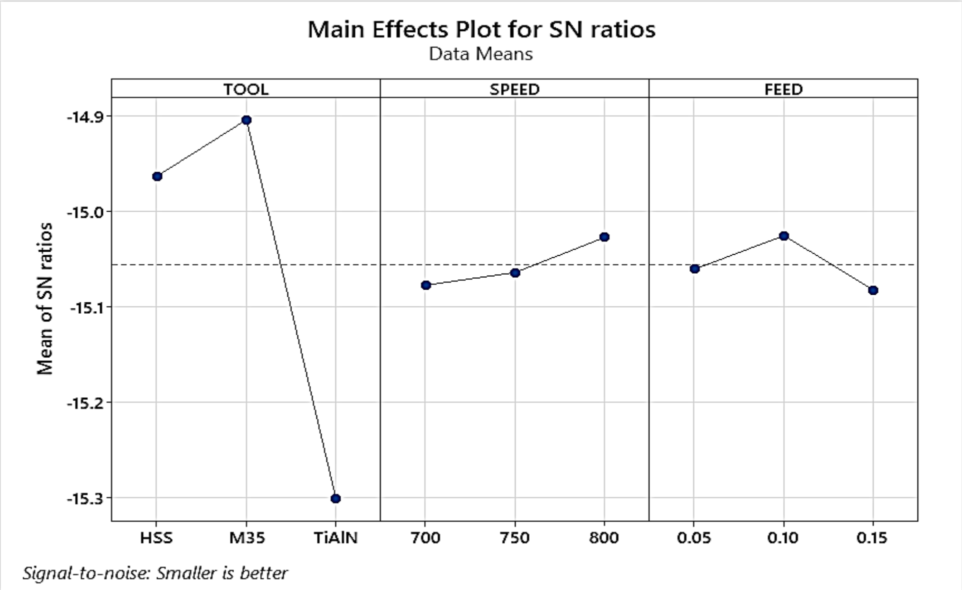


Figure 7. Main effects plot for S/N ratio of diameter

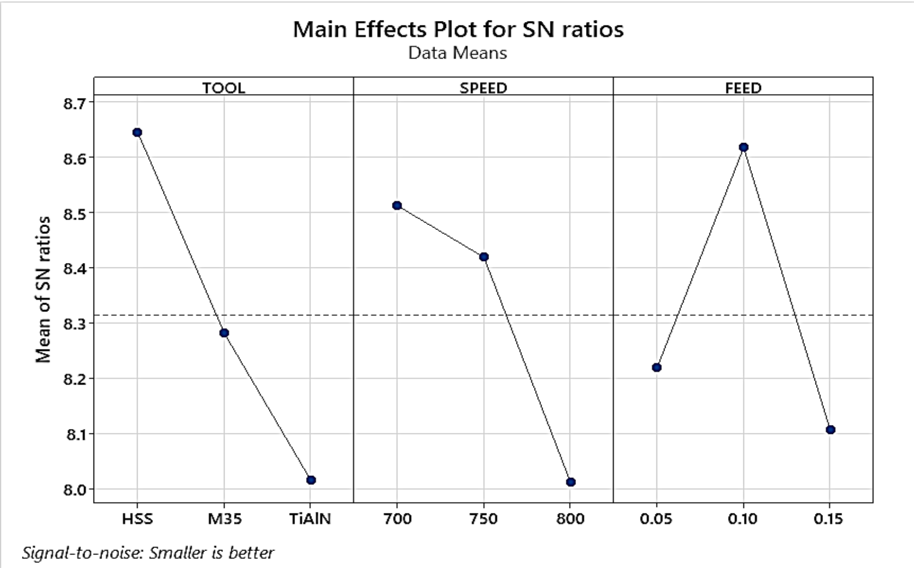


Figure 8. Main effects plot for S/N ratio of perpendicularity

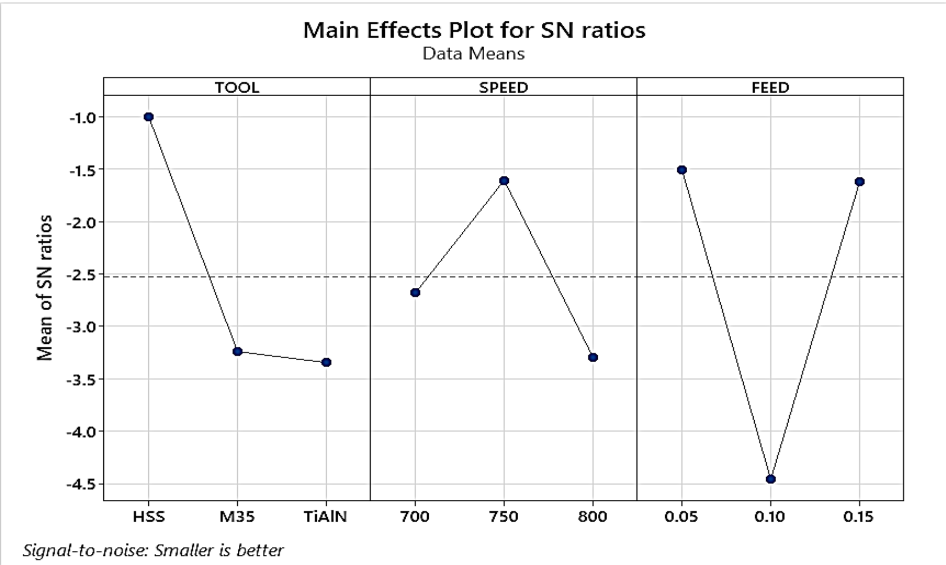


Figure 9. Main effects plot for S/N ratio of surface roughness (Ra)

Figures 5, 6, 7, 8 and 9 show the main effects plot of S/N ratio for roundness, cylindricity, hole diameter, axis perpendicularity and roughness respectively. Based on this, the most suitable combination of drilling speed, feed rate and type of tool may be selected to produce optimum response parameters in the deep hole drilling process. The optimum parameters identified are comparable to published results in [30] and may be stated as follows:

- For minimum roundness, HSS tool, 750rpm, 0.15mm/rev
- For minimum cylindricity, M35 HSS, 750rpm, 0.15mm/rev
- For minimum hole diameter, M35 HSS, 800rpm, 0.10mm/rev
- For minimum axis perpendicularity error, HSS, 700rpm, 0.1mm/rev
- For minimum surface roughness, HSS, 750rpm, 0.05mm/rev

Based on literature review, ANOVA reveals that drilling parameters, cutting-tool material and their coatings significantly influence hole-quality characteristics (i.e) hole size, circularity, cylindricity, and axis perpendicularity [35-37]. The results of regression analysis relating the drilling parameters (speed and feed) with response factors are next presented based on the experimental data collected. Regression equations and standard error of regression (standard deviation) for roundness, cylindricity, hole diameter, axis perpendicularity are as follows.

1) Regression Equation for Roundness vs Speed, Feed: ROUNDNESS = - 0.007 + 0.000037 SPEED - 0.010 FEED

   Standard error of regression=0.01754 and standard error of estimate=1.18%

2) Regression Equation for Cylindricity vs Speed, Feed: CYLINDRICITY = -0.014 + 0.000076 SPEED + 0.057 FEED

   Standard error of regression=0.0283 and standard error of estimate=14%

3) Regression Equation for Diameter vs Speed, Feed: HOLE DIAMETER = 5.899 – 0.00034 SPEED + 0.15 FEED

   Standard error of regression=0.04613 and standard error of estimate=1.05%

4) Regression Equation for Perpendicularity vs Speed, Feed: PERPENDICULARITY = 0.212 + 0.000224 SPEED + 0.047 FEED

   Standard error of regression=0.143475 and standard error of estimate=1.61%

The regression models also show that feed is more influential than speed on roundness, cylindricity, hole diameter, and axial perpendicularity. It can be seen that, speed and feed affect roundness and diameter in the opposite sense whereas they affect the cylindricity and axial perpendicularity in the same sense. The lower values of the standard error of regression equations obtained builds trust in using them as prediction models.

4. Future Work

The range of cutting speed used in the experiments are rather limited and it is needed to fully understand the effect of cutting speed on the process, with necessary care to avoid drill breakage. Longer tool retraction values may be experimented with G83 code, hoping to reduce diameter error and cylindricity errors. Further research will be required to examine the influence of the of drill point angle and tool wear process on the hole quality. Future work will be therefore directed towards the consideration of tool wear, cutting force and torque in optimization of deep hole drilling process. This will affirm cost-effective manufacturing of deep hole drilled components with various materials. Moreover, intelligent optimization techniques such as machine learning including Artificial Neural Networks, are implemented to achieve in-process monitoring of deep hole drilling [38].

5. Conclusion

Several precision engineering parts are characterized by stringent tolerance requirements. Even though tolerance may be within limits, assembly issues arise due to the incorrect geometry of the deep drilled holes. In components made by deep hole drilling, such assembly issues are caused by a variety of geometric tolerances, including circularity, perpendicularity, cylindricity and position inaccuracies. Deep hole drilling requires expensive machine tool set up and serious procedures to be followed. But in this paper, a novel approach to get deep holes drilled using the peck drilling approach of CNC machining is successfully performed and various dimensional and geometric tolerance parameters are verified. In deep hole drilling of AISI 316 steel, the hole size and cylindricity measurements reveal that HSS drills perform better, while TiAlN performed well in maintaining perpendicularity. Chip morphology studies indicate that HSS tools produce thin long chips characteristic of ductile machining, resulting in lower surface roughness. There is always room for adjusting the parameters and optimizing the results with Taguchi techniques, to achieve the optimal values. Optimum parameters for deep hole drilling of AISI316 are obtained through Taguchi optimization for various hole quality metrics. S/N ratio analysis show that the type of cutting tool is the most influential parameter for roundness, cylindricity and diameter, followed by speed and feed.

For perpendicularity, type of tool followed by feed is more influential than speed. For surface roughness, feed is more influential followed by type of tool.

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Acknowledgement

The authors would like to thank VIT University's management and the Dean of the School of Mechanical Engineering at VIT Chennai, India, for their support in carrying out this work.

Authors Contribution Statement

The conceptualization and design of the study were contributed to by all authors. M Sujan Kumar was responsible for material preparation, data collecting, and analysis. M Sujan Kumar wrote the first draft of the manuscript, and all contributors reviewed prior drafts. The final manuscript has been read and approved by both the authors.

Funding

The authors declare that no funds, grants or any other support were received during the preparation of this manuscript.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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Yes

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