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Precision Helical Milling Of AISI 4140 Alloy Steel: An Experimental Study

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ABSTRACT

The two elements considered in the determination of the manufacturing viability of a product include the quality of the surface and the feature tolerances of that product. The core aim of this research work is to perform an experimental investigation to determine the hole accuracy on the AISI 4140 alloy steel with an innovative helical milling process, which is more commonly referred to as "hole production through a helical path milling. In this work, Taguchi's experimental design method is implemented to study the influence of feed rate, cutting speed and axial depth of cut on the surface roughness of the hole as well as geometrical and dimensional tolerances. The goal is to demonstrate that helical milling may serve as a viable substitute for traditional drilling.

Keywords- *Helical Milling, Geometrical and dimensional tolerances, Surface roughness.*

1. INTRODUCTION

The last and final stage in the machined products is the drilling. Small errors accumulated during this operation may lead to nonconforming assembly sets. Zero cutting speed at the center of the drill is one of the primary disadvantages of traditional drilling. At very high thrust cutting forces, it may lead to undesirable situations with tool deflection and dimensional deviation of the hole drilled. Making a hole with a milling tool by rotating this along a helical path is referred to as "helical milling," an entirely new process for making high-quality holes in precision. This method is considered better than standard drilling since it wears edges smoothly, produces smaller axial force and attains high accuracy. Also, conventional drills produce a burr around the hole when the process ends because of the workpiece material's plastic deformation and the drill tool's cutting lip shape. Helical milling's kinematics enable the production of holes with changing diameters without the need for the tool to be changed and hence it ensures substantial adaptability and a reduction in machining time and cost. Therefore, helical milling has been used very extensively in the production of parts for different industries like energy, aircraft and also the excavation machinery [1-3].

The dissipation of heat generated through the hole-making process is highly crucial for creating high-quality holes. Conventional lubrication methods result in increased cutting fluid consumption, inadequate fluid penetration into the cutting zone, and a considerable increase in machining costs. From a different perspective, growing concerns over environmental factors, along with enhanced legislation and regulatory practices, have forced owners of industries to limit the usage of mineral-based lubricants. As a result, various studies are focused on replacing mineral-based cutting fluids with eco-friendly alternatives, as their use will provide better savings and better lubrication performance. Examples of such techniques are: use of solid lubrication, cryogenic technology and using renewable fluids such as those from vegetable sources. [4].

2. Kinematics of Helical Milling

A combination of the tool diameter and the helical path diameter determines the nominal diameter of the final hole in helical milling, despite traditional drilling. According to helical milling kinematics, the cutting tool rotates around its own axis, moves axially, and revolutionizes around the hole axis all at once [5–6]. The three primary components of feed rate in helical milling are (1) the axial feed rate per tooth, (2) the cutting edge's tangential feed rate, and (3) the helix's tangential feed rate, which are determined by equations. (1), (2), and (3) in that order. Equation (4) is used to determine the tangential feed rate tool path. Eqs. (5) and (6) can also be used to determine the helical angle and depth per helical revolution.

$$V_{fha} = f_{za} * z * n \quad (1)$$

$$V_{ft} = f_{zt} * z * n \quad (2)$$

$$V_{fht} = V_{ft} * \left(\frac{h}{D_B}\right) \quad (3)$$

$$V_f = \sqrt{(V^2_{fha} + V^2_{fht})} \quad (4)$$

$$\alpha = arctan\left(\frac{V_{fha}}{V_{fht}}\right) \quad (5)$$

$$a_p = tan(\alpha) * \pi * D_h \quad (6)$$

The end mill number of teeth is denoted by z, the rotational spindle speed per minute by n, the axial and tangential feed rates of each tooth by za and zt, respectively, and the hole diameter and helical path diameter by Dh and DB in these relations. Material removal rate in helical milling increases with the growth of the ratio of hole diameter to the tool diameter. The process will therefore become more efficient as a result. This improvement is constrained by blind holes, though. The operation will not be carried out correctly if the tool diameter is less than half of the hole diameter. Furthermore, cutting forces will rise, resulting in some unintended consequences. Helical milling has a lower chance of built-up edge creation since the cutting region is smaller. Helical milling removes material by cutting instead of extruding, which is different from traditional drilling. As a result, a substantially lower thrust force may be anticipated. The helical milling cutting tool path is the basis for two different types of machining: the front cutting edge of the work piece is machined by the axial feed of the cutting tool, and the peripheric cutting edges, which form the wall of the machined cylindrical hole, are machined by the tangential feed of the cutting tool [7-9].

The helical milling method incorporates two distinct cutting motions at once: a continuous frontal cut on the axial cutting edge, similar to conventional drilling, and a discontinuous peripheral cut, similar to milling. The formation of a discontinuous chip is dependent on these helical milling aspects. The undeformed chip's geometry is displayed in Figure 3 following the tool's rotation at an angle of φ = 180. Here are the geometrical relationships:

$$h_{tan} = f_{zt} * sin(\varphi) \quad (7)$$

$$h_{ax} = f_{za} \quad (8)$$

$$b_{ax} = \frac{Dt}{2} \quad (9)$$

Where htan and hax represent the undeformed chip thickness of milling part and drilling part, respectively; The tangential and axial feeds per tooth are represented as fzt and fza, respectively.; Dt is tool diameter, φ is tool rotational angle; and bax is undeformed chip width.

3. Materials and Equipment

The tests were implemented on AISI 4140 steel alloy cylindrical samples 15 mm height and 23 mm diameter. This alloy's chemical composition is in Table 1. The hardness of 23.5mm diameter rods were found to be 31 HRC (by Brinell hardness test). These rods were austenized at 820°C and then air cooled to a temperature of 410°C. Finally they were oil quenched to obtain a hardness of 39 HRC [10-12].

The experiments were executed on a three axis CNC machine tool of BFW Chakra+ (BMV 60^{+} TC24) model with a FANUC series oi-MF controller Using a down milling method spindle speed of up to 8,000 rpm. 5 mm four-fluted solid carbide end mill tool with 30° helical angle and TiAl coating was utilized (Fig 1).

Table 1: AISI 4140 chemical composition:

C	Cr	Mn	Si	Mo	S	P	Fe
0.38-0.43 %	0.80-1.10 %	0.75-1.0 %	0.15-0.30 %	0.15-0.25 %	0.040 % max	0.035 % max	Balance

where h_{tan} and h_{ax} represent the undeformed chip thickness of milling part and drilling part, respectively; The tangential and axial feeds per tooth are represented as fzt and fza, respectively.; D_t is tool diameter; φ is tool rotational angle; and b_{ax} is undeformed chip width [13].

Fig 1: Solid Carbide End mill

To measure the Geometrical and Dimensional tolerances (Cylindricity, Circularity, Hole nominal diameter), a CARL ZEISS – GERMANY CMM machine with 2mm tangential probe, accuracy of 2.7μm, and ZEISS CALYPSO software had been employed. The workpiece surface was measured in three sections, with a distance of 3, 8, and 13mm.

The helical interpolation milling components were mounted on coordinate measuring machine table, and aligned to machine axes and the measurements were carried out and the parameters were evaluated.

In addition, hole surface roughness was measured with a Marsurf roughness tester. Measurements were carried out within 0.8mm cut off length in 4 in four distinct locations. Ultimately, the average measurement value was reported as the mean surface roughness (Ra) of machined holes [14].

4. Experimental Methods

Based on the Taguchi design method, four criteria were considered in order to streamline experiments and assess important hole-making factor. The parameters are feed rate (fz), axial depth of cut (ap), cutting speed (Vc), and workpiece hardness (H). An overall total of eighteen experiments were carried out using the Taguchi L18 orthogonal array. The factors and levels of the experiments are shown in Table 2. If all experimental cases were evaluated, 21 * 33 = 54 experiments would have been done, which would be time- and cost-intensive. All the experiments were done randomly in order to remove experimental errors. To improve the reliability of results and because of tool wear, the cutting tool was swapped out after each five-hole cycle. In experiment numbers 3 and 4, the Ra values were 0.7102 and 0.4010 correspondingly and Figure 2 displays their hole surface topographies as well as the locations of the 18 holes. [15].

Fig 2: Surface topography of machined holes.

Table 2: The effective parameters and their levels.

Factors	Levels		
	Level 1	**Level 2**	**Level 3**
Workpiece Hardness (H) (HRC)	31	39	-
Cutting Speed (V_c) (m/min)	30	40	50
Feed Rate (f_z) (mm/tooth)	0.01	0.04	0.07
Axial Depth of Cut (ap) (mm)	0.05	0.1	0.15

5. RESULTS AND DISCUSSION

The nominal diameters and tolerances of the holes that were generated were subsequently measured using a CMM instrument, as previously stated. A total of 18 experiments were conducted. Table 3 gives the L18 experimental design array as well as reported tolerances and surface roughness for each experiment. After that, the focus will be on relative output.

5.1 Surface Roughness

'Surface roughness' is a key property in determining the condition of the surface quality and is essential for the components application beneath dynamic loads.

Table 3: L18 design experiment array with relative output

Test no.	H (HRC)	V_c (m/min)	f_z (mm/tooth)	a_p (mm)	Circularity (mm)	Cylindricity (mm)	Hole diameter (mm)	R_a (µm)
S1	31	30	0.01	0.05	0.023	0.042	8.003	0.3891
S2	31	30	0.04	0.1	0.028	0.042	8.017	0.5056
S3	31	30	0.07	0.15	0.025	0.054	8.009	0.7102
S4	31	40	0.01	0.05	0.025	0.046	8.001	0.4010
S5	31	40	0.04	0.1	0.028	0.053	8.021	0.5503
S6	31	40	0.07	0.15	0.022	0.048	8.013	0.5421
S7	31	50	0.01	0.1	0.023	0.038	8.009	0.5100
S8	31	50	0.04	0.15	0.023	0.041	8.029	0.6167
S9	31	50	0.07	0.05	0.023	0.046	8.006	0.6366
H1	39	30	0.01	0.15	0.026	0.053	8.030	0.8023
H2	39	30	0.04	0.05	0.023	0.055	8.003	0.5503
H3	39	30	0.07	0.1	0.024	0.048	8.028	0.6404
H4	39	40	0.01	0.1	0.022	0.048	8.038	0.7336
H5	39	40	0.04	0.15	0.025	0.044	8.024	0.7799
H6	39	40	0.07	0.05	0.023	0.051	8.010	0.5241
H7	39	50	0.01	0.15	0.019	0.025	8.188	0.7091
H8	39	50	0.04	0.05	0.030	0.051	8.085	0.5754
H9	39	50	0.07	0.1	0.025	0.037	8.149	1.2548

The helical milling superiority over conventional drilling methods is demonstrated in Table 3, where the surface irregularity magnitude in all experiments was less than 1.2548 µm. A statistical analysis called the Analysis of Variance (ANOVA) was performed to determine the process variables importance that impacts the roughness of the surface. The significance of each of the primary elements and their relationship to one another can be assessed using ANOVA through the comparison of the mean square values to an estimation of the experimental errors at predetermined confidence levels. All of the primary factors were taken into account at first, together with their two-factor interactions. After that, inconsequential elements were regarded as model errors. The final ANOVA model states that significant factors are indicated by P values less than 0.049 (95% CI).

The findings indicate that each of the primary parameters is considered to be significant. The final model's R2 value for surface roughness estimation was 96.74%, demonstrating the exceptionally high accuracy of the fitting model. In Figure 3, the principal effects of variables on mean surface roughness are highlighted. Figure 3a illustrates that the surface irregularity increases in parallel with the enhancement of the workpiece hardness. This is due to the increased likelihood of a built-up edge, which results in a more nonuniform surface. Figure 3b compares surface roughness to cutting speed. In fact, higher cutting speed leads to increased surface roughness. Therefore, moderate cutting speeds improve surface quality. Surface roughness increases with increase of feed rate, as shown in Figure 3c. As the feed rate increases, the thickness of the undeformed chip actually increases and, subsequently, higher cutting forces result in increased surface roughness. Figure 3d represents that with the increased axial depth of cut the value of surface roughness increases. This is mainly because of higher plowing force involved in the removal of material. The sum of squares of every variable has been divided by the total quantity and multiplied by 100 to determine the percentage contribution of each parameter. The statistical analysis revealed that axial depth of cut, feed rate, hardness and cutting speed have the effect on the roughness of surface by 43%, 39%, 8% and 6% respectively. Figure 4 displays how every variable affects the surface's roughness.

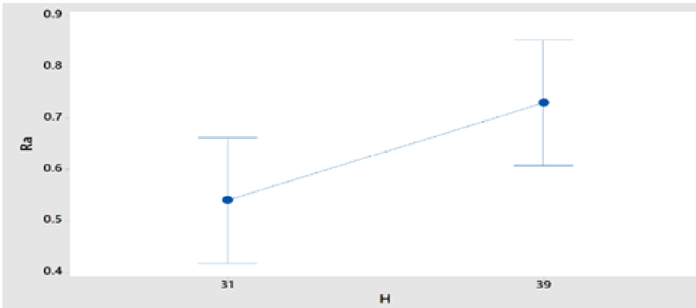

Fig 3a: Hardness's impact on surface roughness

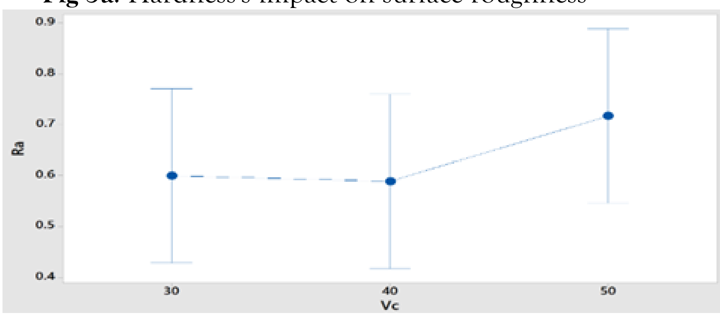

Fig 3b: Cutting speed impact on surface roughness

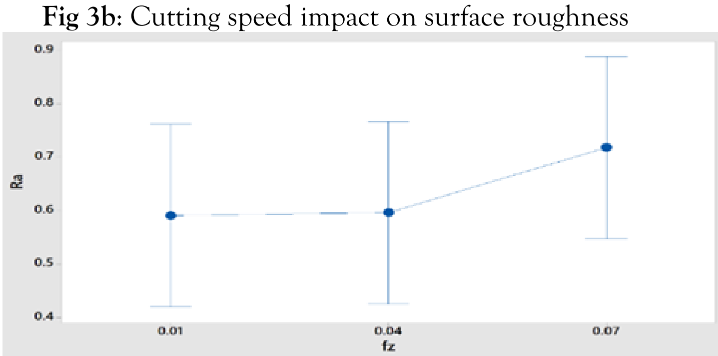

Fig 3c: feed rate impact on surface roughness

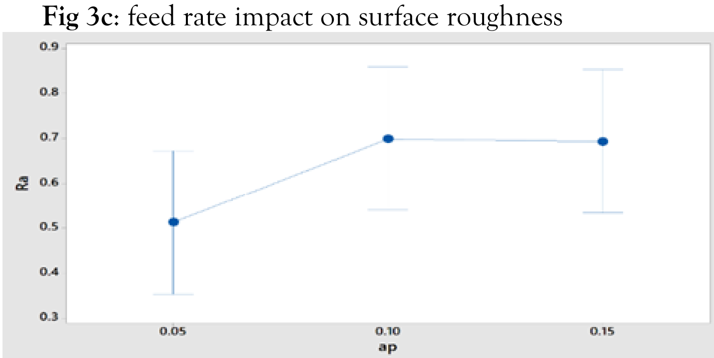

Fig 3d: depth of cut impact on surface roughness

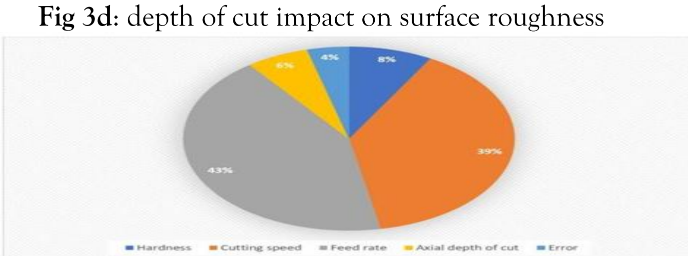

Fig 4: Impact of each parameter (%) on the surface roughness.

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5.2 Hole Nominal Diameter

Cutting parameters have a major impact on the hole nominal diameter, which is also considered to be one of the key components of hole quality. The study's intended hole diameter was 8 mm, therefore the analysis of variance for that parameter took that into account. Similarly, all of the primary factors were crucial to the hole diameter. The impact of the primary variables on the hole nominal size is depicted in Figure 5. It is evident that, regardless of the cutting conditions, the hole diameter varies between 8.001 and 8.188 mm. As shown in Fig. 5a, cutting speed increases hole diameter variations. The variable cutting speed adversely affects the quality of hole. In actuality, a faster cutting speed causes more cutting forces and heat buildup in the cutting region, which causes a deviation in diameter. Figure 5b shows that when feed rate rises, the thickness of the undeformed chip also rises, causing the tool to deflect and the cutting forces to increase. The hole diameter deviates from its stated size as a result. Higher axial depth of cut increases the helical pitch and, consequently, cutting forces, according to the kinematics of the helical milling procedure. Greater cutting forces cause an increase in vibrations and weaken the hole. Figure 5c shows how the axial depth of cut affects the hole nominal size. It is clear from Fig. 5d that bigger differences in hole diameter from the nominal size appear in hard materials. This is because cutting forces and material strength have both increased. Additionally, the harder specimens increase tool deflection and dimensional errors. Figure 6 shows how the factors affect the accuracy of the hole that was produced. The most significant influence on the changes in dimensional tolerance is the cutting speed. Conversely, feed rate, material hardness, and axial depth of cut have the lowest.

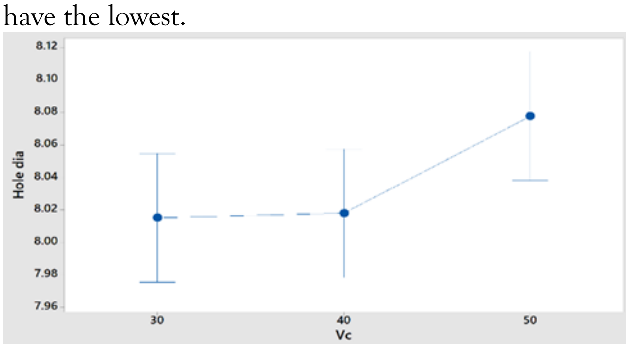

Fig 5a: Effect of cutting speed on hole diameter

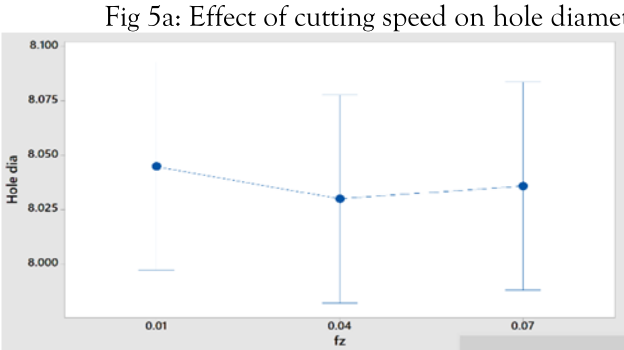

Fig 5b: Feed rate impact on Hole Diameter

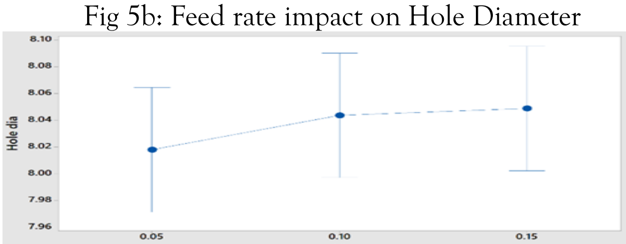

Fig 5c: Axial depth of cut impact on Hole diameter.

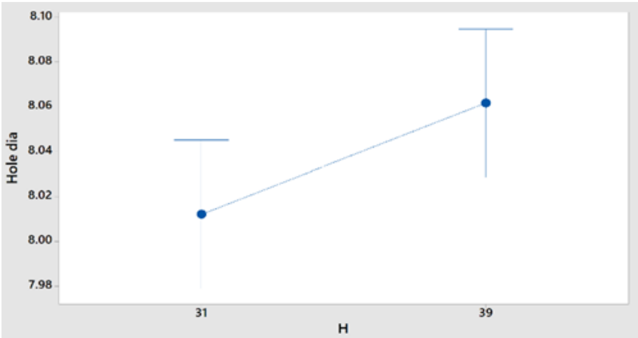

Fig 5d: Hardness impact on hole diameter.

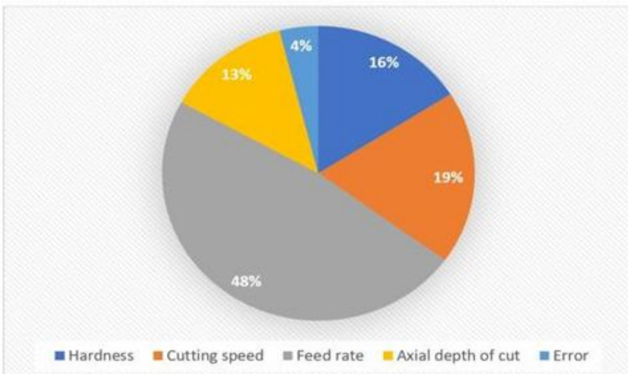

Fig 6: Impact of each parameter(%) on hole diameter.

5.3 Hole Circularity

Circularity describes the level of roundness difference (radial deviation) between the highest and lowest points on a single circle. The study of factors on this tolerance reveals that the biggest deviations with a magnitude of 0.03 mm often occur during low speed helical milling. A P value less than 0.05 tells you which factors are significant. All the important parameters had a significant effect when the model was run. The influence of changes in cutting speed on the circularity of holes is presented in Figure 7a. It is clear that increasing the cutting speed increases this tolerance. This could be due to an improvement in the stability of the process that parallels the influence of cutting speed on dimensional tolerance. Figure 7b also shows the effect of feed rate on hole circularity. It is evident that the dimensional tolerance and the circularity variation trend are comparable. On the other hand, the hole circularity deviation decreases which is visible in Fig. 7c with an enhancement in the axial depth of cut (helical pitch). The contact surface of tool and workpiece in each hole cross section is really improved by a greater axial depth of cut. Therefore, a hole with less deviation in each section is formed. Workpiece hardness's impact on the circularity of hole (Fig. 7d) is comparable to the outcomes described in the preceding section. Furthermore, Fig. 8 shows the impact of individual process variable on the circularity of hole. The parameter that most strongly affects the hole circularity is cutting speed, followed by feed rate, axial depth of cut, and workpiece hardness.

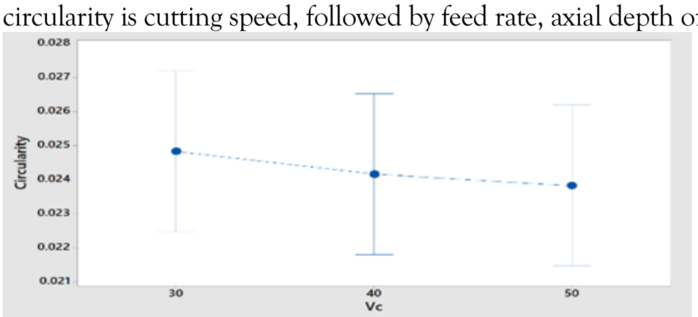

Fig 7a Cutting speed impact on hole circularity

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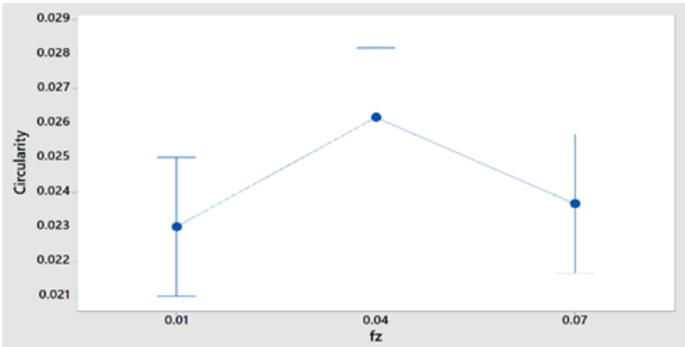

Fig 7b: Feed rate impact on Hole circularity

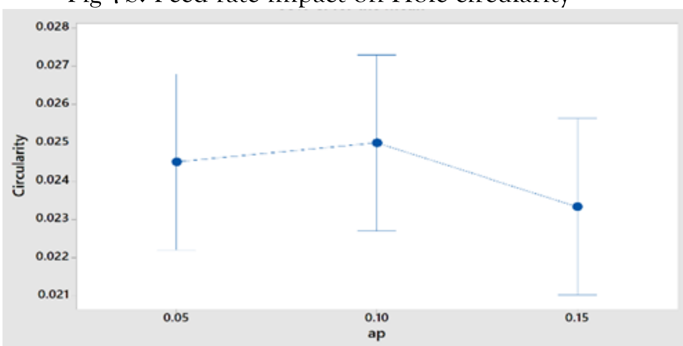

Fig 7c: Axial depth of cut impact on Hole circularity.

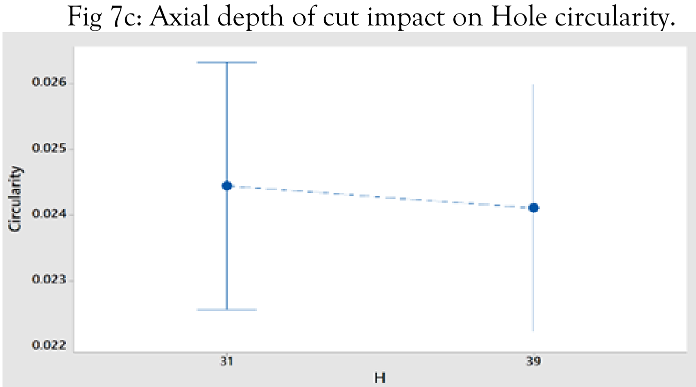

Fig 7d: Effect of hardness on hole circularity.

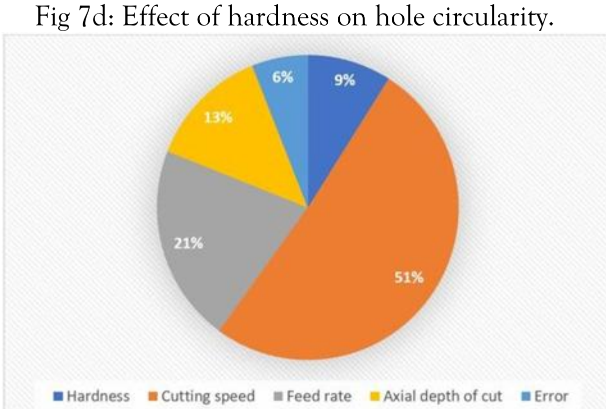

Fig 8: Impact of each parameter(%) on hole circularity.

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5.4 Hole cylindricity

A significant rise in the hole cylindricity magnitude in comparison to circularity tolerance has been found by comparing the results. This rise shows how process factors affect hole axis straightness. Significant factors are identified by the fact that their P values are less than 0.05 (reliability is over 95%). It follows that each factor is significant.

Cutting speed is a key parameter that has a beneficial effect on tolerance, as shown in Fig. 9a, which shows how cutting speed affects hole cylindricity. The effects of feed rate, axial cut depth, and workpiece hardness show comparable patterns to those observed in the instance of circularity as per the Fig. 9b, c, d. The axial depth of cut influence on hole cylindricity were improved, which is the key point that is readily apparent in Fig.9c. As previously stated, this is certainly to be expected since the tool path is shortened, resulting in fewer unintended machine tool movement mistakes and other outside influences. Fig. 10 illustrates how the primary parameters affect hole cylindricity. The depth of the axial cut has twice the original effect. In fact, Circularity and straightness tolerances are actually combined to determine hole cylindricity.

Therefore, it can be understood that the amount and manner of axial depth of cut impact on hole straightness is one of the variables that influences the hole cylindricity by comparing the findings with hole circularity and hole nominal size.

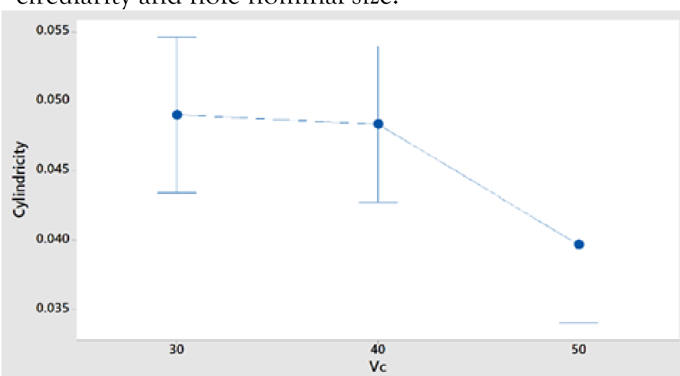

Fig 9a Cutting speed impact on hole cylindricity.

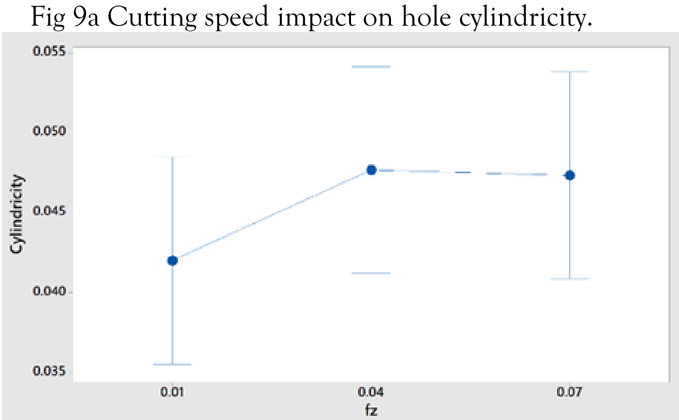

Fig 9b Effect of feed rate on hole cylindricity.

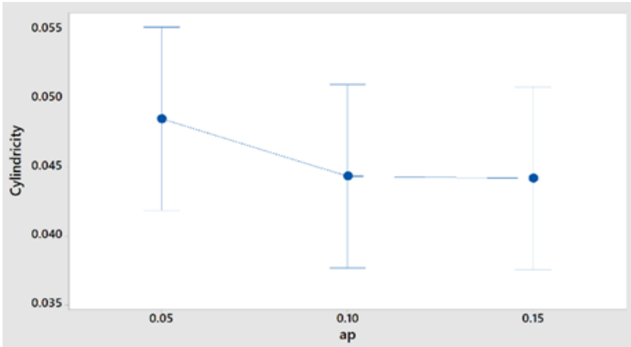

Fig 9c Effect of axial depth on hole cylindricity.

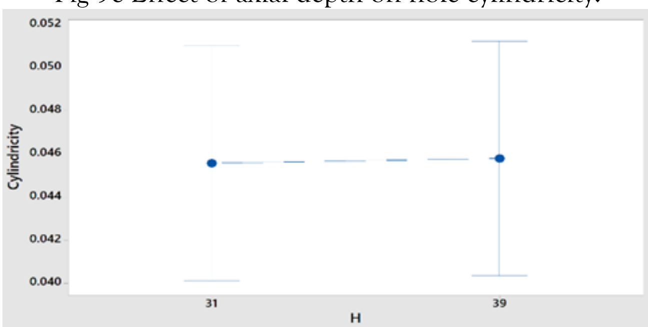

Fig 9d Effect of hardness on hole cylindricity.

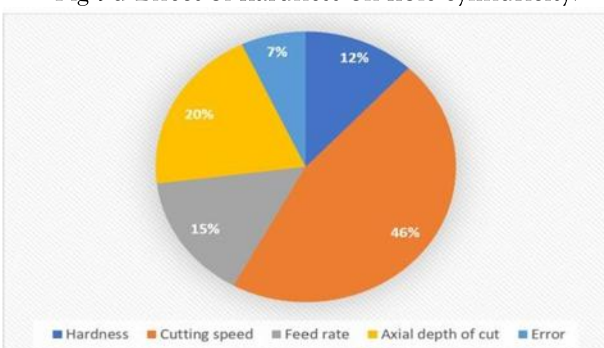

Fig 10: Impact of each parameter(%) on hole cylindricity.

6. CONCLUSION

Helical milling was used in this study as a new way to make holes in AISI 4340 steel. For this reason, how cutting speed, feed rate and axial depth of cut change the hole quality was studied through Taguchi experimental design. The results that were reached are detailed below:

- The cutting speed affected circularity the most, by 51% and cylindricity with 46%. On the contrary, the feed rate was most significant in influencing surface roughness and nominal diameter, with a contribution of 43% and 48% respectively.
- The geometrical tolerances of the created hole are reduced as a result of the shortening of the tool path and the reduction of unwanted errors caused by machine tool movements, as well as the effect on hole cylindricity and other external factors, despite the negative effect of increasing axial depth of cut on hole nominal size.
- Geometrical dimensional tolerances are adversely affected by workpiece hardness as a result of tool deflection.
- Optimal hole quality occurs at 50 m/min, 0.01 mm/tooth feed rate, and 0.1 mm axial cutting depth.

7. Scope for future work

Heat removal is another key of producing high-quality holes. Conventional lubrication techniques do not penetrate the cutting area, increase the cost of machining, and waste cutting fluid. Another approach is that due to environmental concerns, limitations, and legal enforcement, industry owners have reduced mineral-based oil consumption. This has led to a significant number of on-going research studies that focus on replacing environmentally friendly cutting fluids at lower costs and higher lubrication efficiency than the mineral-based cutting fluids. Solid lubrication, cryogenic lubrication and minimal quantity lubrication (MQL) using organic oils such as those from vegetables are some of these methods.

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