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Investigation of the Fluctuation Size in Thrust Force and Chip Morphology in Drilling

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Abstract

Drilling is a widely used production method, having a broad range of applications taking part in machining operations. The length of the cutting edge of the drill causes variations in cutting speed, resulting in undesired outputs. In order to decrease this adverse impact in drilling, selecting higher point angles is an obligation, associated with three different kinds of feed rates and spindle speeds. The aim of this study is to investigate the effect of feed rate, spindle speed, and point angle on the fluctuation size in thrust force besides the effect of the fluctuation size in thrust force on the surface roughness, tool wear and chip morphology. In conclusion, while higher point angles provided optimum outputs such as lower fluctuation size in thrust force, less tool wear, better surface quality and continuous chip form, the effect of feed rate and spindle speed on these outputs varied depending on each other. With the stability in fluctuation size in thrust force, less tool wear took place, and better surface quality and continuous chip form were achieved. However, due to the effect of vibrations, higher fluctuation size in thrust force caused undesired outputs, such as poor surface quality, more tool wear, removal chip in short and brittle form during the drilling operations.

Keywords: Drilling, Thrust force, Tool wear, Chip morphology, Machinability, Surface quality, thrust force fluctuation, Drill point angle.

1. Introduction

Drilling is a manufacturing process, providing desirable, geometrical and dimensional accuracy with the product [1]. Among traditional metal cutting processes, drilling is one of the most important machining methods, including approximately 33% of all metal cutting operations [2]. However, higher precision and quality requirements in the field of the machining restrain the drilling processes due to inclusion of the complexity of the manufacturing and application [3]. Many factors, such as drill point angle, materials of both drill and workpiece, and other selected parameters, such as feed rate, spindle speed and drill tool geometry affect thrust force, surface roughness, chip morphology, magnitude wear of the drill and accuracy of the hole to be drilled [4].

A thrust force is a driving force providing either the remove of the material or the cause of the deformation. The outputs such as tool wear, surface roughness and tool life demonstrate the process quality in machining operations depending on the thrust force [5]. Both the thrust force and torque mainly take place due to the effect of the cutting action, provided by the cutting and chisel edges [6]. Furthermore, these forces, depending on the length of the cutting edge, therefore, are changeable during the drilling processes on the different sections of the cutting edge [7]. The difference in these forces results from the geometry of the tip of the drill and the length of the cutting edge. This variation in thrust force causes chatter vibrations, leading to high noise levels and tool wear, damaging the surface quality and decreasing the tool life [8]. Moreover, these vibrations are the major reason for drill tool wear and tool failure in deep drill operations [9, 10]. Cutting forces, depending on the mechanical properties of the machined material such as, drilling parameters, number of drill flutes, drill radius, drill geometrical structures and selected parameters, such as spindle speed, feed rate, cutting depth and tool geometry cause the differences in thrust force values [11]. Especially, great fluctuations in thrust forces in harmonic deviation take place in the drilling of layered structural materials [12]. At the beginning of the process, when the tip of the drill starts to penetrate into the workpiece, the fluctuation size in thrust force reaches its highest levels, and after falling a little, it remains stable [13]. The orientation of drill tip, which is created by the point angle, causes specific cutting pressure as a geometrical parameter in the process. Therefore, the point angle of the drill has a major impact on the thrust force [3]. Additionally, a pre-drilled pilot hole is largely reduced by thrust force [14]. Consequently, reduction in the thrust force improves the surface quality and reduces the power consumption [15].

Better results are achieved at low cutting conditions, while undesired results are attained at excessive drilling conditions [16]. The thrust force and torque are diminishable by 40% via selecting the optimum parameters. However, at higher feed rates, the thrust forces increase due to the increase of the pressure load on the drill, but this pressure decreases with increase in the spindle speed [17, 18]. The selection of improper parameters causes brittle behavior in both workpiece and chips with the effect of the shear deformation of the workpiece [19]. At higher spindle speeds and lower feed rates, this unfavorable effect can be eliminated [20]. Furthermore, the effect of the feed rate on the process is bigger than the spindle speed. Because higher feed rates cause higher removed chip area and in this case, higher thrust forces take place [21]. Thus, the feed rate is a consequential influential parameter on the quality characteristics [6]. The thrust force values increase with increasing drilling depth but decrease with increasing the drill point angle [22].

Surface roughness is an important output in displaying the dimensional accuracy and the surface quality in machining processes. While the spindle speed has a positive effect on the surface quality, the effect of the feed rate is negative [23]. Because when the spindle speed increases, more heat is generated; and this generation provides the workpiece material to soften and yield high surface quality [24]. However, at higher feed rates, the surface is deteriorated by the chip marks [25, 26]. Moreover, the chip, removed from the shear zone, affects the surface quality in drilling [27].

Chip morphology is a complex process since it includes both elastic and plastic deformations, reflecting the breaking behavior of the material. According to this behavior, three kinds of chip shapes are generated because of ductile and brittle breaking. These forms are continuous, adherent and discontinuous. With improperly selected parameters, the chip is removed in brittle and short forms, while continuous form is achieved with properly selected parameters [28]. At lower feed rates, but higher spindle speeds, and point angles, chips are achieved in the continuous, ductile and longer forms indicating the better results, while at higher feed rates, lower point angles, namely at extreme drilling conditions; chips are occurred in brittle and short forms depending on increase in the hardness [29, 30]. However, a mixture of chip sizes usually indicates that two cutting-edges angles and their lengths on both sides are different [31].

According to the literature, the thrust force and the fluctuation size in thrust force are the major influential parameters on the outputs, such as surface roughness, tool wear and chip formation in machining processes. Although the drilling method has a wide usage area in industrial machining manufacturing operations, there is a major problem with the natural geometry of the tip of the drill, whose main reason is the variation in cutting speed along the length of the cutting edge changing in relation with the drill point angle. The variation in cutting speed causes severe tool wear, poor surface quality and short the tool life. These undesired outputs are the major problems in industrial manufacturing. In order to contribute solving this problem, the fluctuation size in thrust force was investigated according to the feed rate, spindle speed and point angle. Additionally, the outputs, such as surface roughness, tool wear and chip morphology were analyzed according to the fluctuation size in thrust force in the drilling of a pre-drilled pilot hole of AISI 1050 steel alloy.

2. Materials and Methods

Experiments were performed on MEXUS 510 C-II Model Mazak Vertical Center CNC Milling machine, as shown in Figure 1 (a). The AISI 1050 alloy samples were prepared in dimensions of 100 mm x 100 mm x 15 mm. The mechanical properties and chemical composition of AISI 1050 steel alloy were demonstrated in Table 2 and Table 3, respectively. The holes were pre-drilled 5 mm in diameter and 13 mm in depth as pilot holes, at 1600 rpm spindle speed and 0.01 mm/rev feed rate. However, in the experimental procedure, each hole was drilled only 10 mm in diameter and 10 mm in depth due to the dynamometer, fastened under the samples. Furthermore, the plan of the experiments and selected parameters, as seen in Table 1, was provided with experiment no and order. The separation distance between the centers of the holes adjusted as 20 mm, but the center of the first hole was adjusted 10 mm from the corner of the material. HSS drill tools 10 mm in diameter, were ground at 100°, 118°, 136°, and 154° point angles, as seen in Figure 1 (d), using grinder machine as seen in Figure 1 (c).

The thrust force values, in the direction of the drill proceeding into the work piece, were measured in Newton unit via Kistler 5233A dynamometer as shown in Figure 1 (b). With the help of a computer, the datum, gained from the data logger, was saved. The drill surfaces, cutting edges, chips and flute faces of the drills were also analyzed by the metallographic studies. A Stereo, LEICA Z16 APO model microscope was employed for this purpose. The surface roughness of the drilled holes was measured by using TR 200 TIME SIRF surface roughness device at a sampling of 0.8 mm. The graphs were designed by using Minitab software. Besides, in analyzing the nested ANOVA modeling, the same software program was used.

Figure 1. Experimental Setup a) Milling Machine, b) Kistler Type 5233 dynamometer data logger, c) tool grinder machine, d) drills with different point angles.

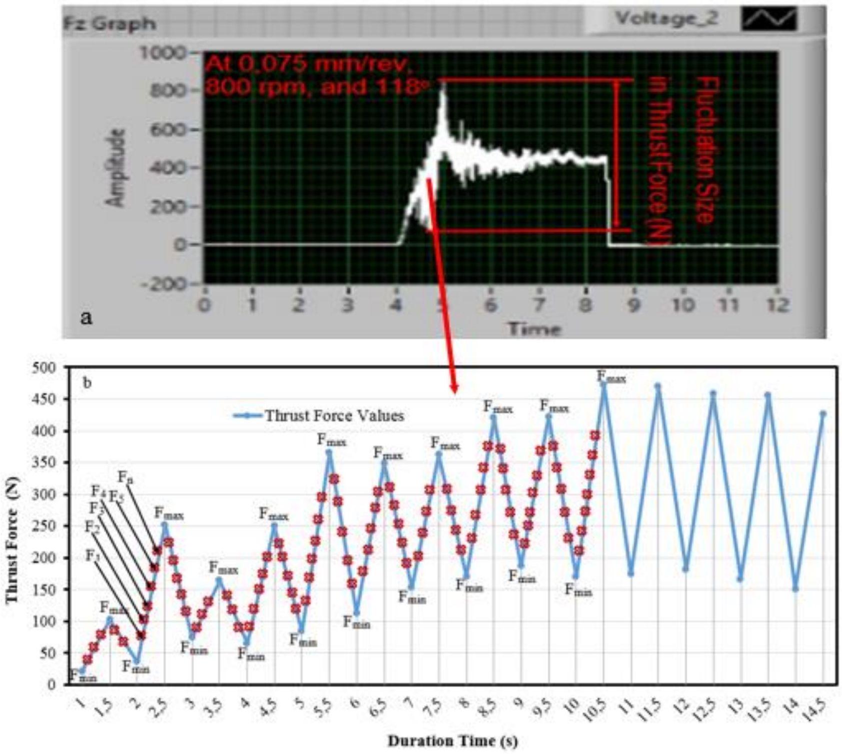


Figure 2. Fluctuation size in thrust force a) graph achieved from a dynamometer, b) calculated thrust force values in one-second time.

The deviation sizes in thrust force were obtained by using Kistler 5233 A-model dynamometer, as seen in Figure 2 (a). By the help of a data logger, from the beginning of the process until the drill tool started regurgitating, the hundreds of these force values were saved, (as seen in Figure 2 (b), Fmin, F_1, F_2, …. F_n, and Fmax) in every one-second of time. In analyzing the fluctuation size, only one minimum and one maximum of these values were taken into account for per unit of a second time during the drilling operation. Due to the aim of this study, only one minimum and the maximum thrust force values were selected for each second of the process, as seen in Figure 2 (b). By using these values, the fluctuation size in thrust force was calculated for each second time of the process, according to the Equation 1. Then the arithmetical average of these values was calculated in percentage for only one experiment set up. In this way, the fluctuation size in thrust force was also calculated for all selected parameters separately.

Fluctuation in thrust force is calculable as in equation 2.1.

$$(\%)_{1\mathrm{Second}} = \frac{(\mathrm{F_{max}} - \mathrm{F_{min}})}{\mathrm{F_{max}}} . 100 \qquad \textbf{(2.1)}$$

Table 1. The experiments' plan.

Experiment No	Spindle Speed (n) (rpm)	Point Angle (Φ) (°)	Feed Rate (f) (mm/rev)
1	800	100	0,025
2	1200	100	0,025
3	1600	100	0,025
4	800	118	0,025
5	1200	118	0,025
6	1600	118	0,025
7	800	136	0,025
8	1200	136	0,025
9	1600	136	0,025
10	800	154	0,025
11	1200	154	0,025
12	1600	154	0,025
13	800	100	0,050
14	1200	100	0,050
15	1600	100	0,050
16	800	118	0,050
17	1200	118	0,050
18	1600	118	0,050
19	800	136	0,050
20	1200	136	0,050
21	1600	136	0,050
22	800	154	0,050
23	1200	154	0,050
24	1600	154	0,050
25	800	100	0,075
26	1200	100	0,075
27	1600	100	0,075
28	800	118	0,075
29	1200	118	0,075
30	1600	118	0,075
31	800	136	0,075
32	1200	136	0,075
33	1600	136	0,075
34	800	154	0,075
35	1200	154	0,075
36	1600	154	0,075

Table 2. Mechanical properties of AISI 1050 alloy.

Properties Name	Values
Hardness (HB)	229
Ultimate Tensile Strength (Mpa)	725
Ultimate Tensile Strength (Mpa)	415
Elongation at Break (%)	20
Reduction of Area (%)	40
Modulus of Elasticity (Gpa)	205
Bulk Modulus (Gpa)	160
Poisson Ratio	0.29
Shear Modulus (Gpa)	80
Density (g/cc)	7.85
Specific Heat Capacity (J/g°C)	0.486
Thermal Conductivity (W/mK)	49.8

Table 3. Chemical composition of AISI 1050 alloy.

Component Element Name	Values (%)
Carbon (C)	$0.47 - 0.55$
Iron (Fe)	$98.46 - 98.92$
Manganese (Mn)	$0.60 - 0.90$
Phosphorous (P)	≤ 0.040
Sulphur (S)	≤ 0.050

3. Mathematical Approach to the Chip Formation

The geometry of the drill has a major effect on the drilling processes. The point angle of the tip of the drill provides the shape of the cutting edge. Therefore, the point angle has an important impact on the drilling operations. However, the length of the cutting edge is a problem due to the conical shape of the tip of the drill, so is the variation in cutting speed along the cutting edge. Because of the geometry of the drill, the cutting speed takes a maximum value at the periphery of the drill, but it approaches zero near the centerline of the drill [20]. The geometrical modeling of the cutting edge of a drill, as shown in Figure 3, Ødo is the symbol of the pre-drilled pilot hole diameter and Ødh is the drill diameter. 2w is the length of the chisel edge, F_{t1} and Ft2 are the tangential forces, F_{z1} and F_{z2} are the thrust forces on the first and second cutting edge of the drill, respectively. F_{y1} and F_{y2} are the radial forces in the direction of the revolving of the drill. F_{zc}-1 and F_{zc}-2 are the thrust forces on the chisel edge. ψ_c is the chisel edge angle. φ is the half value of the point angle specifiable as Φ/2 (Φ_1, Φ_2, Φ_3, Φ_4 and selected in this study as 100°, 118°, 136°, 154°, respectively. The thickness of the un-deformed chip (h_D) can be calculated geometrically depending on the feed rate (f_z) and one-half point angle (φ) by using equation

3.1 according to the geometrical shape, as seen in Figure 3 (b).

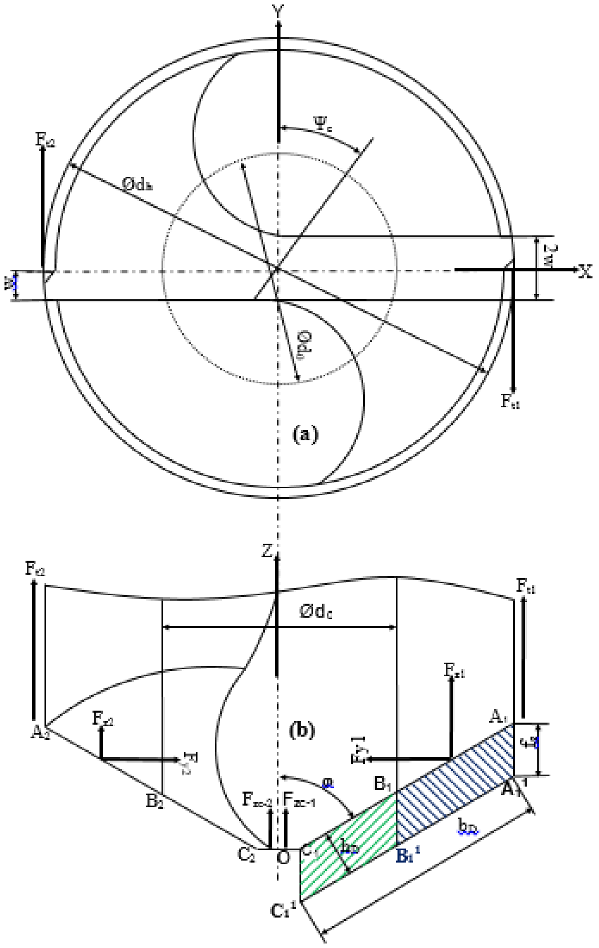


Figure 3. Geometry of the tip of the drill a) the top view, b) the front view [32, 33].

$$h_D = f_z . \cos\varphi \text{ (mm)} \quad \textbf{(3.1)}$$

The AISI 1050 steel alloy samples were pre-drilled 5 mm (Ødo) in diameter, as a pilot hole. In the circumstances, in pre-drilling conditions, the length of the cutting edge, namely the width of the un-deformed chip is identified as (h_D), calculated by using equation 3.2.

$$l = |C_1A_1| = b_D = \frac{d_h - d_o}{2.\sin\varphi} \text{ (mm)} \quad \textbf{(3.2)}$$

Under the circumstances, the effective un-deformed chip area (Ac) can be calculated depending on the effective un-deformed chip width (b_D) and thickness (h_D), as seen in equation 3.3.

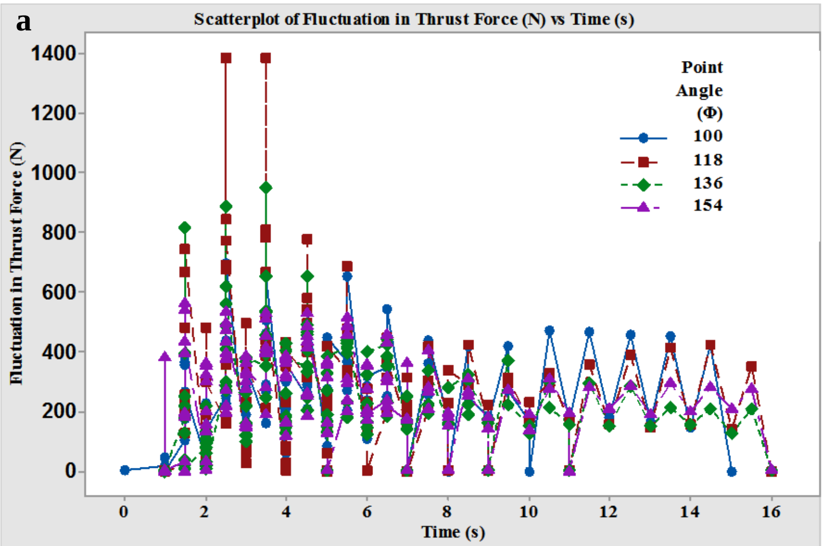
$$A_c = A_c|B_1B_1{}^1 - A_1A_1{}^1| = h_D . b_D \text{ (mm)}^2 \quad \textbf{(3.3)}$$

As seen in Figure 3, equations 2, 3, and 4, the geometrical dimensions of the chip, such as chip thickness, chip width and chip area depend on the geometry of the tip of the drill, especially, drill point angle and pre-drilled hole diameter [32, 33].

4. Results and Discussion

4.1 Fluctuation in Thrust Force and Surface Roughness

In order to determine the effect of the selected parameters on the fluctuation size in thrust force, also the effect of the fluctuation size in thrust force on the surface roughness, the holes were pre-drilled 5 mm in diameter. AISI 1050 steel alloy samples were drilled using HSS drills 10 mm in diameter at various spindle speeds, feed rates and drill point angles. The effect of the point angle, the spindle speed and the feed rate on the fluctuation size in thrust force are shown in Figure 4 a, b, and c, respectively depending on the time in the second unit, during the drilling process. Moreover, the variation in the fluctuation size in thrust force, depending on the feed rate, the spindle speed, the point angle and the effect of the fluctuation size in thrust force on the surface roughness can be seen in Figure 4 d.



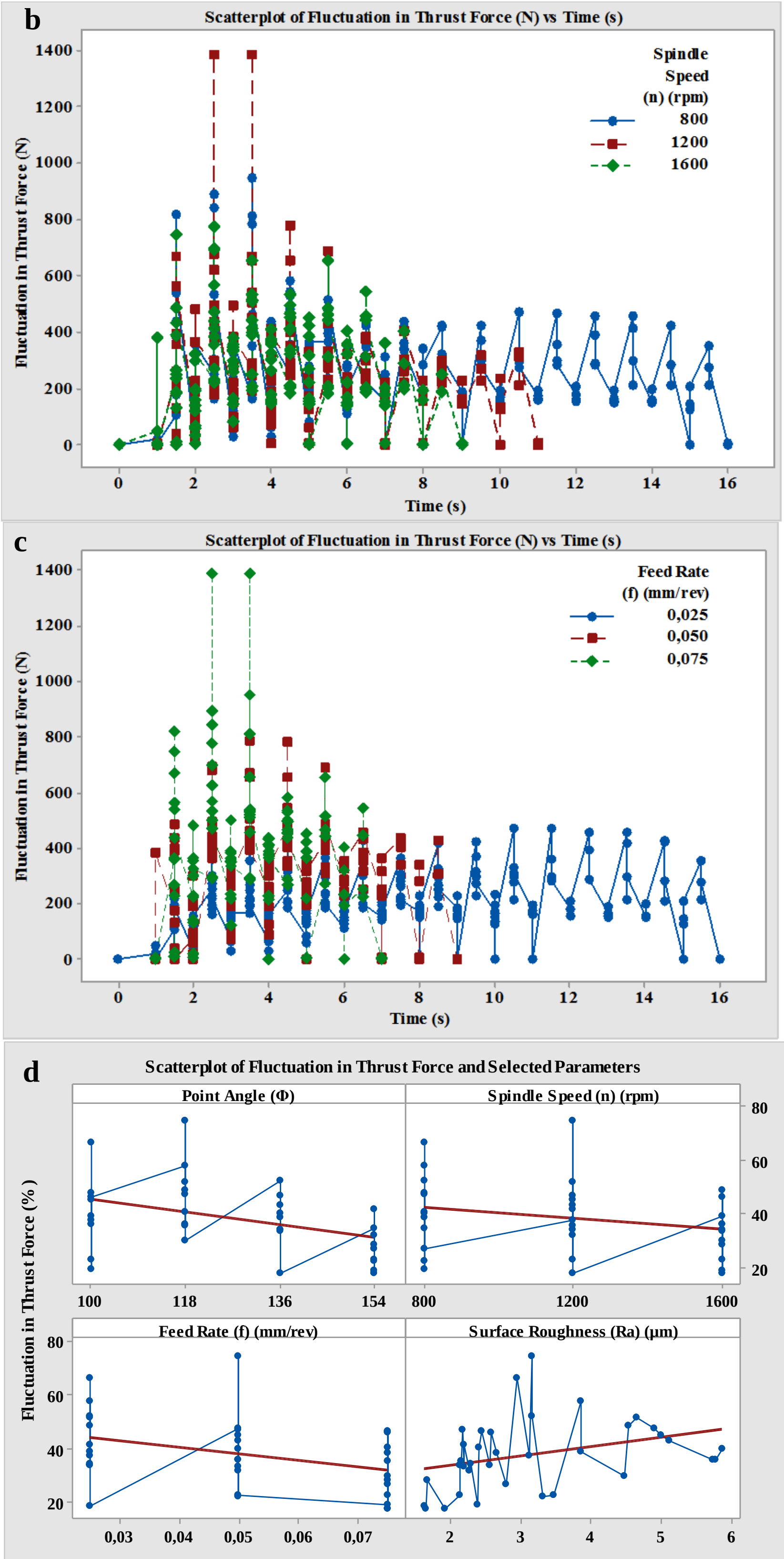


Figure 4. The fluctuation size in thrust force (%) a, b, and c) depending on duration time, d) fluctuation size in thrust force relative to feed rate, spindle speed, point angle, and surface roughness (µm).

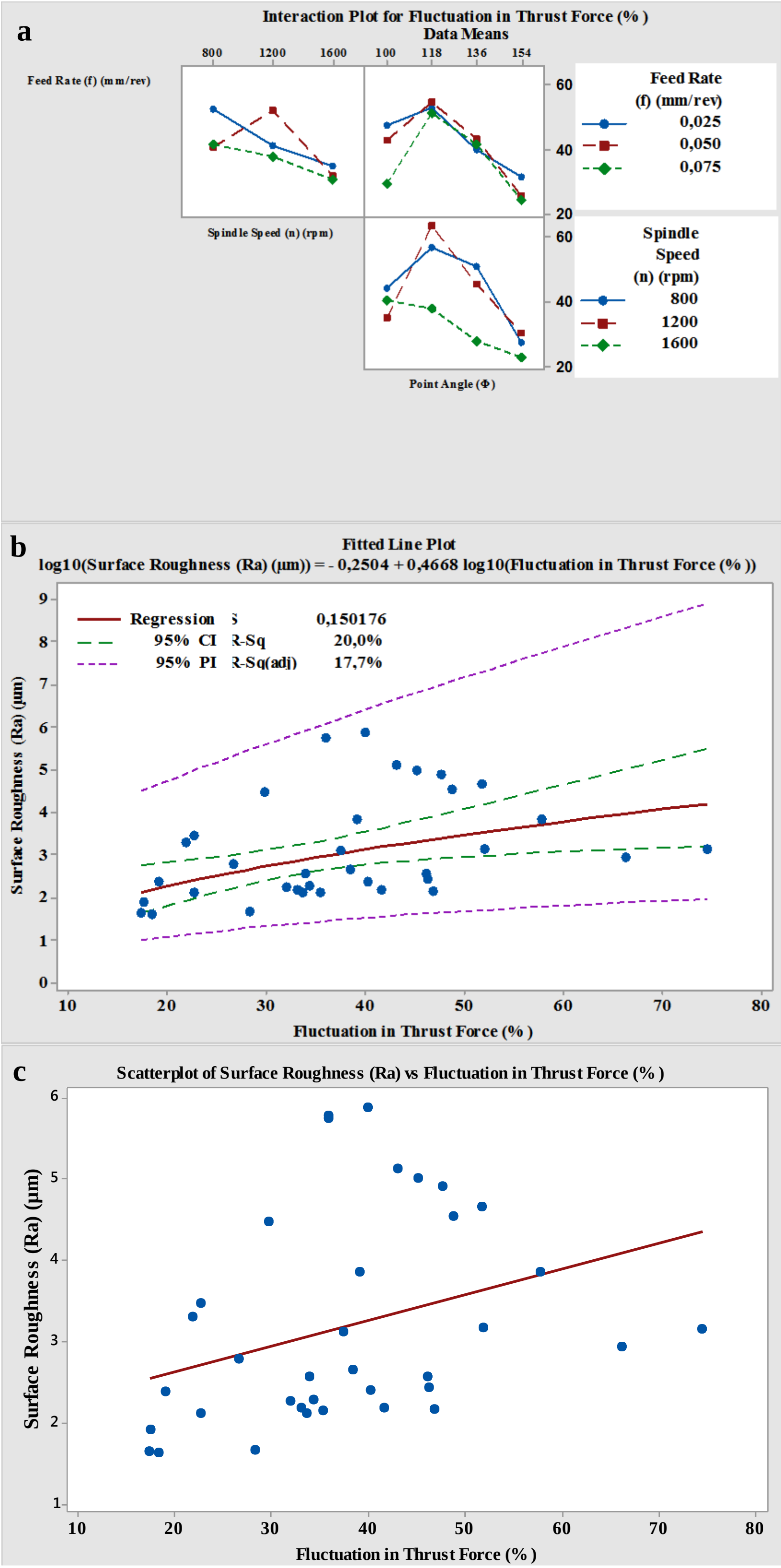
Usually, increase in the point angle causes decrease in removal chip dimensions and especially, chip area according to Equations 2, 3, and 4. Less removal chip area means smaller thrust force, lower percentage of the fluctuation size and better outputs. Therefore, increase in the point angle provides lower percentage of the fluctuation size in thrust force, namely less vibration and lower thrust forces during the process, as seen in Figure 4 (a). The first effect of the spindle speeds and feed rates is shortened the processing time. The ending time of the drilling process was recorded as 7, 9, and 16 seconds at 0.025, 0.050, and 0.075 rev/mm feed rates, respectively, but these values were 9, 11, and 16 seconds at 800, 1200, and 1600 rpm spindle speeds, respectively, as well. These results show that the effect of the feed rate is more than the spindle speed on the processing time. The second, increase in the spindle speed and decrease in feed rate was caused less by the fluctuation size values, as can be seen in Figure 4 (b and c), respectively. The highest fluctuation values appeared at the beginning of the drilling when the tip of the drill penetrated into the workpiece; then it remained stable [19]. As seen in Figure 4 (a, b, and c), at the beginning of the drilling process, when the tip of the drill contacted to the workpiece, the fluctuation size values were higher. However, after the variation in the fluctuation size values decreased, they showed more stable alteration until the end of the process. Thus, the lowest fluctuation size values in thrust force were recorded at 0,025 mm/rev feed rate, 1600 rpm spindle speed, and 154^o point angle.

Figure 4 d shows the effect of the feed rate, the spindle speed and the point angle on the fluctuation size values. Generally, with increase in all of these parameters, the fluctuation size values decreased linearly. However, the most influential parameter was point angle, followed by the feed rate and spindle speed, respectively. In other words, the least influential parameter on the fluctuation size values was spindle speed. In machining operations, chip dimensions, chip area is the most influential parameter on the process forces. Therefore, the chip dimensions depend on point angle, feed rate and drill diameter, but they do not depend on spindle speed, as seen in Equations 2, 3, and 4. In this case, the effect of the spindle speed on the fluctuation size values probably resulted from the rotating motion of the drill. The least fluctuation size in thrust force values were recorded at 1600 rpm spindle speed, 0,025 mm/rev, and 154^o point angle, as 18,40%, also at 0,075 mm/rev feed rate, 136^o point angle, as 17,43%. These results show that the effect of the feed rate on the fluctuation size is changeable depending on the spindle speed and the drill point angle.

Higher fluctuation size values show vibrations consisting, indicating undesired results of the process, such as poor surface quality, severe tool wear and shorter tool life. Naturally, in the circumstances, increase in the fluctuation size values causes the increase in the surface roughness. According to the average graph line in red color, as seen in Figure 4 d, with increase in the fluctuation size values, generally the surface roughness increased linearly. At 1600 rpm spindle speed, 0,025 mm/rev feed rate, and 154^o point angle, the recorded fluctuation size and the surface roughness values were 18,40% and 1,629 µm, at 0,075 mm/rev feed rate and 136^o point angle 17,43% and 1,644 µm, at 0,075 mm/rev feed rate and 154^o point angle 28,38% and 1,672 µm, respectively. These outputs show that the surface roughness depends on the point angle and the spindle speed; accordingly, the optimum surface roughness values were recorded at higher point angles and spindle speeds. The effect of the feed rate on the surface roughness is changeable depending on the point angle and the spindle speed.

According to the 2nd, 3rd and 4th Equations, the feed rate and the point angle have a major impact on the chip thickness and width, namely chip area; accordingly, they mainly affect the fluctuation size in thrust force, individually. Nevertheless, the spindle speed only has an effect on the fluctuation size in thrust force due to the rotating motion of the drill, so the effect of the selected parameters on the fluctuation size can be evaluated with the interaction of them, as seen in Figure 5 (a). At 0,025 mm/rev feed rate, with increasing the spindle speed, the fluctuation size decreased regularly, but at 0,050 mm/rev feed rate it increased. However, at 0,075 mm/rev feed rate, it did not display an important alteration. However, at point angles, bigger than 118^o, for all selected feed rates and spindle speeds, the fluctuation size values reduced linearly. Consequently, the smallest fluctuation size values were recorded at 1600 rpm spindle speed, 136^o, and 154^o point angles, as 17,43% and 18,40%, respectively.

The fitted line plots of the fluctuation size and the surface roughness are as seen in Figure 5 (b and c). The fitted line plot of variation in surface roughness observed a convenience at 95% according to the fluctuation size in thrust force. The average regression in the surface roughness increased regularly with increasing in the fluctuation size in thrust force. These rises were seen for S, R-Sq, and R-Sq (adj) results, as well. The log10 equation of surface roughness was observed above of the graphs. The surface roughness can be calculated approximately by using this Equation. Furthermore, the surface roughness observation shows a linear increase with increasing in the fluctuation size in thrust force. The main effect on plot of the feed rate, the spindle speed and the point angle on the fluctuation size can be seen as in Figure 5 d. The fluctuation size in thrust force decreased with increasing in the feed rate, the spindle speed and the point angle. Especially, at feed rates bigger than 0,050 mm/rev, spindle speeds 1200 rpm and point angles 118^o, the fluctuation size showed a linear, also severe decrease.


a
Interaction Plot for Fluctuation in Thrust Force (%)
Data Means
Feed Rate (f) (mm/rev)
Spindle Speed (n) (rpm)
Point Angle (Φ)
Feed Rate (f) (mm/rev)
0,025
0,050
0,075
Spindle Speed (n) (rpm)
800
1200
1600
b
Fitted Line Plot
log10(Surface Roughness (Ra) (µm)) = - 0,2504 + 0,4668 log10(Fluctuation in Thrust Force (%))
Regression
95% CI
95% PI
S 0,150176
R-Sq 20,0%
R-Sq(adj) 17,7%
Surface Roughness (Ra) (µm)
Fluctuation in Thrust Force (%)
c
Scatterplot of Surface Roughness (Ra) vs Fluctuation in Thrust Force (%)
Surface Roughness (Ra) (µm)
Fluctuation in Thrust Force (%)

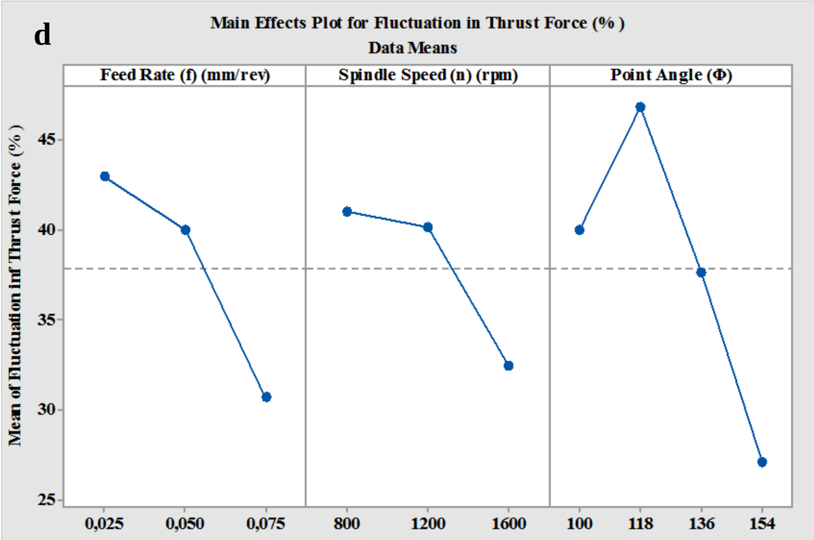


Figure 5. a) The interaction plot for fluctuation in thrust force (%) depending on parameters, b) The variation of surface roughness (µm) depending on fluctuation in thrust force (%) c) fitted-line plot orthogonal regression analysis d) the main effect for fluctuation in thrust force (%) depending on selected parameters.

The point angle of the drill has a major effect on the thrust force, due to the effect of it on the quantity of the removal chip area, in per revolve of cutting [3]. The fluctuation versus in the thrust force, achieved by using Nested ANOVA modeling, can be seen in Table 4. In modeling, the effect of selected parameters on the fluctuation size was analyzed in couples of parameters, such as point angle-feed rate, point angle-spindle speed and spindle speed-feed rate. According to these results, the most influential parameter couple on the fluctuation size was point angle-feed rate taken into account and the P value for point angle was 0,002. Only the P value for point angle was smaller than 0,05. The P values of other parameter couples, spindle speed and feed rate were recorded as 0,059, 0,076, and 0,716, bigger than 0,05. These results showed that the most influential parameter on the fluctuation size values in thrust force was drill point angle, followed by feed rate and spindle speed, respectively.

Table 4 Nested ANOVA fluctuation versus.

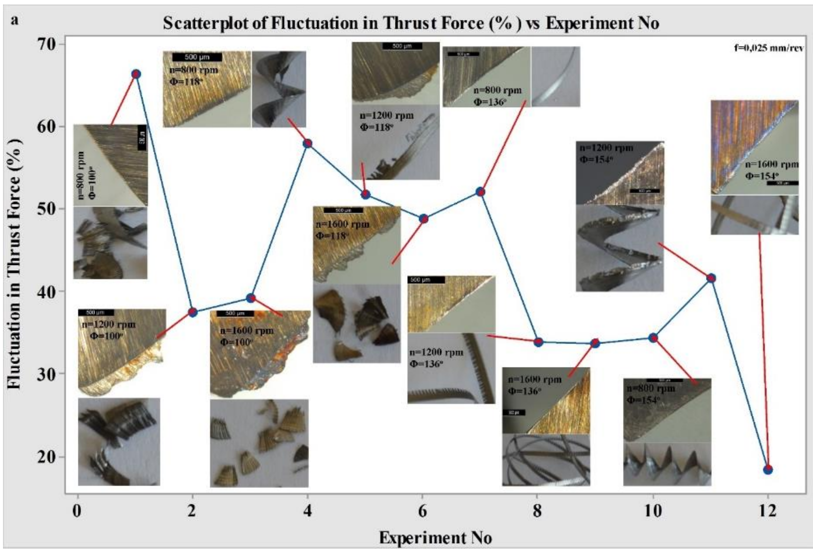
Nested ANOVA Fluctuation in Thrust Force (%). As the Effect Parameters: Point Angle & Feed Rate									
Source	DF	SS	MS	F	P	Var. Comp.	% of Total	St Dev	Experimental Mean Square
Point Angle	3	3019,06	1006,35	12,07	0,002	102,56	35,54	10,13	1,00(3)+3,00 (2)+9,00(1)
Feed Rate	8	666,89	83,36	0,45	0,88	-34,21	0,00	0,00	1,00(3)+3,00 (2)
Spindle Speed	24	4464,00	186,00			186,00	64,46	13,64	1,00(3)
Total	35	8149,95				288,56		16,99	
Nested ANOVA Fluctuation in Thrust Force (%). As the Effect Parameters: Point Angle & Spindle Speed									
Source	DF	SS	MS	F	P	Var. Comp.	% of Total	St Dev	Experimental Mean Square
Point Angle	3	3019,06	1006,35	3,79	0,059	82,30	32,36	9,07	1,00(3)+3,00 (2)+9,00(1)
Spindle Speed	8	2125,60	265,70	2,12	0,074	46,831	18,41	6,84	1,00(3)+3,00 (2)
Feed Rate	24	3005,28	125,22			125,22	49,23	11,19	1,00(3)
Total	35	8149,95				254,34		19,95	

Nested ANOVA Fluctuation in Thrust Force (%). As the Effect Parameters: Spindle Speed & Feed Rate									
Source	DF	SS	MS	F	P	Var. Comp.	% of Total	St Dev	Experimental Mean Square
Spindle Speed	2	1145,86	573,93	4,08	0,076	36,05	13,64	6,00	1,00(3)+3,00 (2)+9,00(1)
Feed Rate	6	841,99	140,33	0,62	0,716	-21,97	0,00	0,00	1,00(3)+3,00 (2)
Point Angle	27	6162,10	228,23			228,2	86,36	15,11	1,00(3)
Total	35	8149,95				264,3		16,26	

4.2 The effect of fluctuation size of thrust force on tool wear and chip morphology

The experiments' plan was demonstrated in Table 1 according to the selected parameters. The graph of the fluctuation size in thrust force values was derived according to this plan as seen in Figure 6 (a, b, and c). There were 36 experiments, realized in this study. The fluctuation size in the thrust force was investigated depending on the realized experiments number. Figure 6 (a, b, and c) show the effect of the fluctuation size in thrust force on the tool wear and the chip morphology at 0.025, 0.050, and 0.075 mm/rev feed rates, respectively, also for all selected remaining parameters. Furthermore, the wear region and burning marks on the cutting edges of the drill can be seen in Figure 6 a, b, and c, depending on experiment order number.

At 0.025 mm/rev feed rate, the effect of the spindle speed and drill point angle was investigated as shown in Figure 6 (a). Increasing the spindle speed causes more generated heat in the process. Besides, higher generated heat causes to soften and trigger the severe tool wear, together with the workpiece and drill tool, as well [7, 28]. Accordingly, increasing the spindle speed causes more generated heat triggering the drill tool wear at 100° and 118° point angles according to the experimental studies in the literature. Because at lower point angles, according to the tip of the drill geometry, as specified in 2nd, 3rd, and 4th Equations, the length of the cutting edge, hence the removal chip area, the contact area between the cutting edge and the workpiece increase. At lower point angles, the contact area between drill tool and workpiece increased, hence this high contact was triggered to increase the generated heat, caused severe tool wear, which brittles and shortens chip form. At 136° and 154° point angles even at higher spindle speeds, the magnitude of the tool wear decreased, also the chips were removed in continuous, ductile and longer forms, due to the reducing the chip area, namely contact area between the tool and the workpiece, more of which is desired in machining operations. Therefore, at higher point angles, the least fluctuation size values in the thrust force were gained. Accordingly, decrease in the fluctuation size in thrust force provided less tool wear, longer tool life and more desired chip morphology.



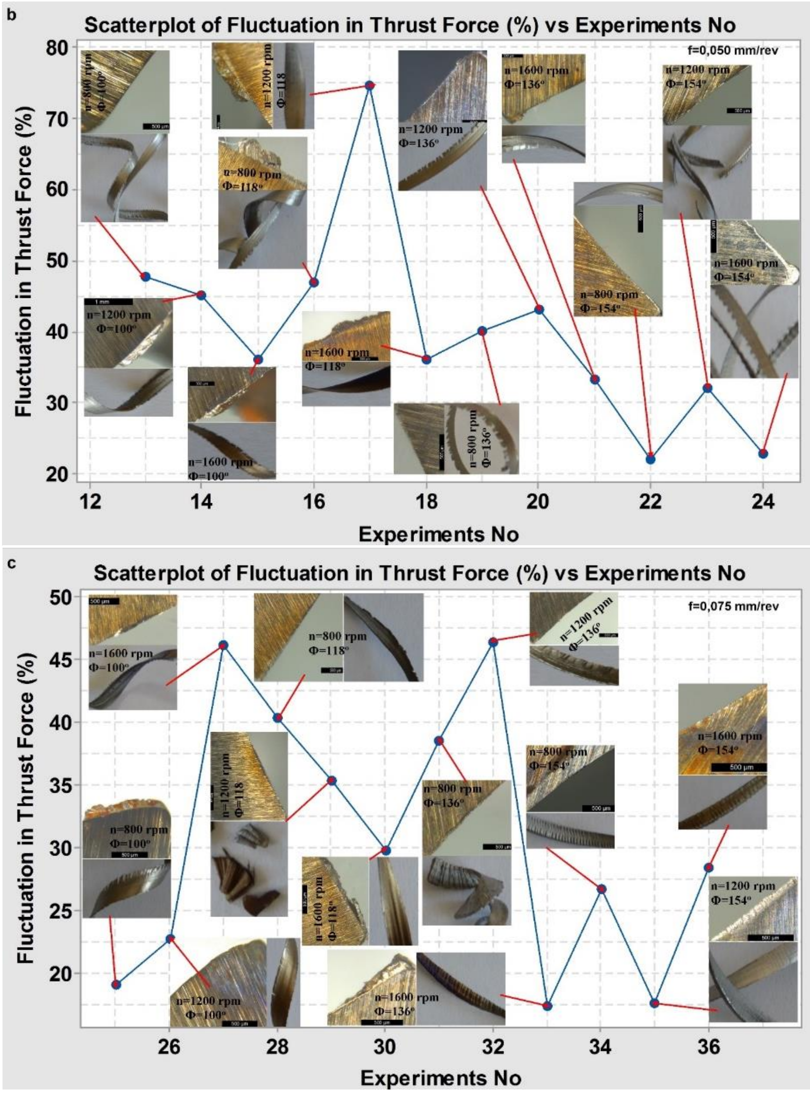


Figure 6. The effect of fluctuation size on both tool wear and chip morphology a, b and c depending on experiment number given in order in Table 1.

However, at higher spindle speeds and point angles, there were burn marks on both cutting edges and also on the removed chips even at 800 rpm spindle speed, but at 100º and 118º point angles. Additionally, they transformed the tool wear and the chipping forms on the cutting edge, even at higher point angles (136º and 154º), 1200 and 1600 rpm spindle speeds.

Tool wear was scarcely observed at 0,050 mm/rev feed rate, 100º point angle and at 800 rpm spindle speed but, at 1200 and 1600 rpm spindle speeds, tool wear increased and the percentage of the fluctuation size in thrust force changed between 30% - 40%. This shows that the change in thrust force did not show any effect on the tool wear at 100º point angle. Although the magnitude of the tool wear displayed surplus at 100º point angle, 1200, and 1600 rpm spindles speeds, the removed chips were gained in the continuous, ductile, and longer form. At 118º point angle, the tool wear increased and the fluctuation size was around 50%, besides, at 800 rpm spindle speed, the chips removed in the long and spiral shape, but at 1200 rpm spindle speed, the fluctuation size increased together with the tool wear, also the chips were removed in the mixture forms including both short and long. However, at 1600 rpm spindle speed, the fluctuation size in the thrust force was decreased, the removed chip was gained in the longer form, and there were burn marks on both cutting edges and the removed chip due to high generated heat of the process. At 136º point angle, especially, together with decreasing the fluctuation size, tool wear was decreased and the chips were formed in the longer form, at lower spindle speeds. At 154º point angle, 800 and 1600 rpm spindle speeds the tool wear and the fluctuation size values decreased, the removed chips were gained in the longer shape. Although better results gained at 154º point angles, at 1200 rpm spindle speed, there were burn marks on the cutting edges and little increasing in the fluctuation size, also chips were gained in the middle size. Consequently, 0,050 mm/rev feed rate and 1200 rpm spindle speed showed an improper effect.

Although the maximum fluctuation size in the thrust force was around 70% at 0,025 and 0,050 mm/rev feed rates, but it was around 45% at 0,075 mm/rev feed rate. As seen in Figure6 (c), less tool wear was observed together with longer chip form, at 100° point angle, and at 800 rpm point angle, but there were small deformation cracks on the removed chip. At 1200 rpm spindle speed the tool wear increased and the chips were removed in the mixture size both in long and short shapes. However, at 1600 rpm spindle speed, the burn marks generated on the cutting edge and the chip was achieved in continuous form, also higher fluctuation size in the thrust force was recorded about 45%. However, at 118° point angle, the fluctuation size decreased, and there were burn marks on the cutting edges and chips due to increase in the spindle speed. Nevertheless, at 1600 rpm spindle speed, the tool wear was reduced and the chips were removed in continuous form without burn marks and deformation cracks. Although smaller fluctuation size was recorded, the tool wear increased, and the deformation cracks occurred on the chips at 1600 rpm spindle speed and at 136° point angle, but less drill tool wear was observed at 154° point angle at 800 and 1200 rpm spindle speeds. These outputs show that higher feed rates lead to severe tool wear at higher spindle speeds due to the insufficient cutting-edge length to remove the chip from the workpiece in per revolution of the drill tool.

In general, the desired results were recorded at higher point angles, lower feed rates-spindle speeds and higher feed rates-spindle speed parameters couples. The least tool wear and the most desired removed chip morphology in continuous shape were gained at 154° point angle, 0,025 mm/rev feed rate-800 rpm spindle speed, 0,050 mm/rev feed rate-1200 rpm spindle speed couples. Although the change in the thrust force did not appear to have a regular effect on the tool wear, it influenced the shape of the chip due to its vibrational effect and ensured that the chip was in the short form. However, at higher feed rates, bigger than 0,050 mm/rev, together with higher the point angle than 154°, were not convenient to achieve the desired results in drilling operations.

5. Conclusions

This paper has explored the effect of the selected parameters on the fluctuation size in thrust force, and also the effect of the fluctuation size in thrust force on the surface roughness, drill tool wear and chip morphology in the drilling of pre-drilled AISI 1050 steel alloy samples by using HSS drill tools. The following results can be derived from this experimental study.

Drill point angle affected the dimensions of the removed chip, such as thickness, width and hence chip area directly. Increase in the point angle meant less chip area, thrust force, fluctuation size in thrust force, namely fewer vibrations in the process and better drilling outputs.

The effect of the feed rate on the processing time was more than the effect of the spindle speed.

At the beginning of the drilling process, the fluctuation size, namely the vibration effect was high, afterwards, during the drill when tool was pushed forward into the workpiece, it decreased and then it showed a stable alteration.

The fluctuation size in the thrust force and the surface roughness showed a collateral alteration depending on the selected parameters. The most desired fluctuation size and the surface roughness values were recorded at 0,025 mm/rev feed rate, 1600 rpm spindle speed, and 154° point angle, as 18,40% and 1,629 µm, respectively. Additionally, at 136° point angle, 1600 rpm spindle speed, and 0,075 mm/rev feed rate they were also recorded as 17,43% and 1,644 µm, respectively.

The effect of the feed rate on the surface roughness was varied depending on the point angle and the spindle speed.

Higher point angles provided less fluctuation size in thrust force, thus smaller fluctuation size in thrust force was provided, also less tool wear and more desired chip forms, such as continuous, ductile, and longer chips were achieved in the machining operations.

According to the chip morphology criteria, the most appropriate parameters were investigated as 154° point angle, 0,025 mm/rev feed rate-800 rpm spindle speed and 0,050 mm/rev feed rate-1200 rpm spindle speed parameter couples. Increase in the fluctuation size in thrust force led to gain removed chips in short and brittle form due to the vibration effect of the drill tool.

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