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Investigation of Burr Formation and Tool Wear During the Drilling of Commercial Purity Copper Material

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Abstract

Copper is one of the materials that are sought and requested in many sectors due to its high electrical and thermal conductivity values. Its high ductility makes it difficult to drill commercial purity copper and has a negative effect on hole quality. In this study, commercial purity copper material was subjected to drilling tests with HSS drills without using coolant. Surface roughness, deviation from diameter and deviation from cylindrical values were measured in varying drilling conditions and also modeled by regression analysis. Quantitative effects of the results were determined by analysis of variance. Also, wears occurring in the drill bits, burr formations at the entrance and exiting of the hole were examined. As a result of the regression analysis, it was observed that the feed rate on the surface roughness value, the coating status for the deviation from cylindrical and diameter had a significant effect on the results ($P<0.05$). It was observed that burrs formation in the hole entrances was insignificantly small, but the burrs formation increased at high feed rate values at the end of the holes, and decreased at high cutting speeds. It has been determined that the workpiece material tends to stick to the drill bits at increasing values of the feed rate and removal of the chips becomes difficult.

Keywords: Burr formation, copper, drilling, regression analysis, tool wear

1. Introduction

Although copper has been used in many fields due to its softness and easy workability in the past, it has found newly apply areas with its newly known properties. It is used extensively in the field of electricity and electronics, thanks to its ability to conduction the highest heat and electricity, especially after silver and gold [1-4]. Although pure copper has high electrical and thermal conductivity, its mechanical properties such as tensile stress, creep and hardness are low [3, 5]. Copper and alloys have been used as bearing materials for a long time due to their properties such as good corrosion resistance, high thermal and electrical conductivity, self-lubrication (by powder metallurgy method) and good wear resistance [6, 7].

Despite the developments in the production methods, the traditional machining methods (turning, milling, drilling etc.) are still up to date. Drilling is still a widely used method with its simple structure and low production costs [8].

Although there are many studies on forming copper materials by machining, studies on drilling are rarely found in the literature. Lin and Ting investigated tool wear with the help of signals based on cutting forces that occurred during the drilling of copper alloy material with HSS drill bits. They stated that the feed rate, depth of cut and tool wear are effective on the cutting forces, and tool wear increases with increasing feed force and moment [9]. Yang et al. they have made drilling tests with two different drill geometries on printed circuit boards. They examined cutting force, torque and chip morphology at different cutting parameters. They expressed that the cutting force increases with increasing feed rate and decreases with increasing cutting speed. They expressed that the drill geometry was significantly effective on thrust force and chip evacuation [10]. Vergara et al. copper and brass materials have been subjected to a series of experiments by friction drilling method. They examined the hole qualities in terms of sheet thickness, spindle speed, feed amount, tool geometry. They explained that high spindle speeds and low feed rates are more effective than other parameters to produce sufficient quality holes

[11]. Tang et al. compared the results with experimental studies by analyzing the drilling of electronic circuit boards with high copper content in terms of cutting force, cutting torque and tool temperature with the help of finite elements. They expressed that the results they obtained from analysis and experimental studies were quite close and consistent [12]. Moriwaki et al. in the turning process of copper material with diamond cutting tools, they studied the deformations that occurred on the cutting tool and workpiece by using experimental and finite element method. They stated that the experimental and simulation results were consistent and that the temperature effect should not be neglected in micro machining with diamond cutting tools [13]. Zhang and zhang investigated the factors affecting surface quality in turning of high conductivity copper material that has undergone various heat treatment processes. They measured the lowest surface roughness values from the samples subjected to recrystallization annealing. In addition, they explained that the homogeneity of the crystalline structure and the order of processing affected the roughness of the finished surface and residual surface stresse [14]. Breton et al. tried to explain the relationship between cutting conditions and surface integrity and related physical-chemical properties in machining. They examined the effects of pure copper material on the electrochemical behavior and corrosion resistance at the end of the super finishing by experimental and finite element method. They presented a model including thermal-mechanical, microstructure, recrystallization approaches to calculate the residual stress, temperature and burr formation areas in the processed material. They compared the experimental and simulation results and stated that the results are compatible with each other [15]. Mahajan et al. have been made a series of turning experiments with high-conductivity copper material with diamond cutting tools. They tried to determine the quantitative effect of four machining parameters on the surface roughness of copper: cutting speed, amount of feed, depth of cut and tool nose radius. From experimental studies, they stated that the tool nose radius is a very dominant parameter among other parameters considered, as well as higher cutting depth, higher cutting speed and higher feed rate can be used as the larger tool nose radius is used [16]. Tanaka et al. examined the chips formed during the turning of the copper material with the diamond cutting tools and the wear mechanisms that occur in the cutting tool exposed to thermal loads. They expressed that the micro cracks formed in the cutting tool formed rapidly by the reaction of the cutting tool material and copper [17]. Shimada et al. have simulated the cutting tool wear mechanisms, thermodynamic loads and wear process when turning copper with diamond cutting tool in oxygen atmosphere. As a result of the study, they stated that turning in the oxygen atmosphere significantly reduced cutting tool wear and increased production efficiency [18]. Rahman et al. studied milling mechanism and factors affecting the micro-end mill cutting tool during the milling of the pure copper workpiece. In their experiments used different cutting speeds, cutting depths and feed rates, they used cutting tools with two different helix angles. They stated that the chips formed at the end of the work was very similar to the chips formed (spiral and broken) during the traditional milling. They stated that tool wear increases with machining time and has a significant effect on cutting forces [19].

Although copper is one of the materials with the highest heat conductivity coefficient, its ductile ductility makes drilling difficult. According to the literature research conducted, the deviation of the holes formed by the drilling of copper materials from the dimensional and geometric tolerances and the interaction of the burr formation with the drilling parameters and drill bit angle are rarely studied. In this study, commercial grade copper material with HSS cutting tools has been subjected to drilling tests at 4 different cutting speeds, 4 different feed rates, 4 different drill bit angles and 2 different coating conditions. The holes formed as a result of the experiment were examined in terms of surface roughness, deviation from the diameter, deviation from cylindrical and burr formation. Also, wears occurring in drill bits were investigated.

2. Materials and Methods

2.1. Material and Machining Experiments

Some properties of commercial purity copper material used in the experiments are given in Table 1. The test part prepared with Ø60 mm diameter and 15 mm thickness is connected to the table of Arion IMM-600 CNC vertical center table with a 4-jaw chuck. Average surface roughness values (Ra) were obtained using Mitutoyo SJ-410 profilometer.

Table 1. Some properties of commercial purity copper [20].

Property	Unit	Copper
Density (at 20ºC)	g/cm^3	7.764
Melting point	ºC	1083.2-
Vickers hardness	HV	50
Yield stress	MPa	33.3
Tensile stress	MPa	210
Elastic modulus	GPa	110
Poisson’s ratio	-	0.343
Heat transmission	[W/(mK)]	385

Generally high precision is required for the parts used in defence and aerospace industries. Therefore, geometric and dimensional tolerances of the holes on these parts are of quite importance. Deviation from diameter is the difference between the nominal diameter and measured diameter of the drilled hole while, cylindricity is defined as the combination of parallelism, circularity and straightness of a cylinder surface. The deviation from cylindricity is the variation between measured

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cylindrical surface and its ideal cylindrical surface [21]. In each measurement, the probe touched four points along the periphery. The measurements were taken 3 mm below and above the top and bottom surfaces of the workpiece, respectively. Deviation from the diameter and the cylindrical measurements has made with Hexagon Global Advantage CMM device. For observation of tool wear and burr formation, a microscope which has LED lighting, a resolution of 5 megapixels with a resolution of 2592x1944, a brightness reduction feature, and a digital 240 magnification feature were used. In Figure 1, the design of the experimental setup established is tried to be shown.

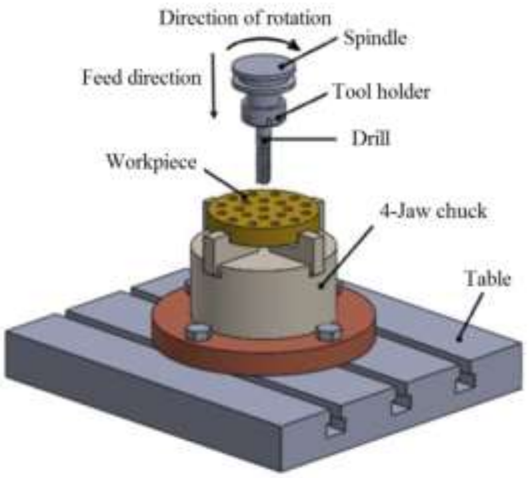

Figure 1. Experimental setup.

Drill bits (drill bit angle: 90º, 105º, 118 ° and 140º) are connected to the tool holder with a Ø5-6 mm collet. Uncoated and coated (CVD - AlTiN - coating thickness: 5 µm) HSS drill bit is shown in Figure 2.

Figure 2. HSS drill bit.

15 mm length hole drilling was applied to the test material by using different cutting conditions with HSS drill bits. The results were examined in terms of surface roughness (Ra), deviation from diameter (DD), deviation from cylindrical (CD), cutting tool wear and burr formation. Experiments are designed with the help of L16 orthogonal array, and the variables and levels used in the experiments are given in Table 2. Variables and levels for the relevant material were determined taking into account cutting tool catalogs and literature recommendations. Preliminary experiments have been carried out at the highest levels of cutting parameters recommended in the catalogs and literature. Statistical calculations such as regression analysis and ANOVA were made by Minitab 17 software.

Table 2. Variables used in the experiments and their levels

Control factors	Cutting speed (Vc)	Feed rate (f)	Drill bit angle (β)	Coating condition (CC)
Unit	m/min	mm/rev	º	-
Code	A	B	C	D
Levels	10	0.025	90	Uncoated
	20	0.050	105	
	30	0.075	118	Coated
	40	0.100	140	

2.2. Regression Analysis

Regression analysis is a model that includes dependent variables (quality characteristic) and independent variables (control factors), and it is enabled the dependent variables to be expressed with independent variables [22]. The coefficient of determination (R^2) obtained as a result of the equation gives the rate of expression of independent variables with dependent variables. The closer the R^2 value to 1, the more accurate results will can be obtained from the regression model.

Regression analysis is a well-known and widely used statistical tool by scientists. Karaca examined the effect of drilling parameters such as cutting speed, feed rate and drill bit angle on the deformation factor formed in the drilling process in glass fiber reinforced plastic composites. It has tried to determine the most appropriate drilling parameters using multiple regression analysis [23]. In the drilling process of fiber-reinforced polymer matrix composite materials, Bayraktar and Turgut investigated the surface damage at the entry and exit of the hole, taking into account factors such as cutting tool, cutting parameters and cutting tool geometry. The data they obtained were tried to be interpreted using methods such as Taguchi, variance analysis, artificial neural networks and regression analysis. They has emphasized that high cutting speed and low feed rates should be used as a result of the studies [24]. Meral et al., have modeled the progression forces and surface roughnesses obtained in the drilling of AISI 1050 material depending on experimental parameters, (such as drill geometry drill diameter, feed amount and cutting speed) with linear regression, quadratic regression and exponential regression methods [25].

3. Results and Discussion

It used 4 different cutting speeds, 4 different feed rates, 4 different drill bit angles and 2 different coating conditions were used in the hole drilling experiments performed on commercially pure copper material. Experimental results are interpreted in terms of average surface roughness, deviation from diameter and deviation from cylindrical values (Table 3).

It obtained as a result of drilling the commercial purity copper material with the determined control factors is the average of the surface roughness 3.202 µm, the average of deviation from the diameter is 0.033 mm and the average of deviation from the cylindrical value is 0.039 mm. When Table 3 is examined, it is seen that the highest values of the variables are 4.178 µm for surface roughness, 0.053 mm for diameter deviation value, 0.060 mm for deviation from cylindrical value. Also, the lowest values are 2.490 µm for surface roughness, 0.015 mm for deviation from the diameter and 0.020 mm for deviation from the cylindrical value. These values are within acceptable limits for rough surface holes at N9-N10 surface tolerances. These differences between the results are an indication that the variables used in the drilling experiments have a significant effect on the drilling performance. The measured average surface roughness is relatively high. The reason for this is that copper used as test material is thought to be of high purity and parallel to its ductility.

When the obtained results are examined in terms of cutting parameters (cutting speed and feed rate); the highest values for surface roughness, deviation from diameter and deviation from cylindrical are measured at a cutting speed of 40 m/min at a feed rate of 0.100 mm/rev. The lowest measurements were obtained at 0.025 mm/rev feed rate at 10 m/min cutting speed for surface roughness value, and at 0.025 mm/rev feed rate at 20 m/min cutting speed at the lowest deviation from diameter and cylindrical values. According to these results, it can be said that surface roughness, deviation from diameter and cylindrical values are affected by the change in cutting parameters. High surface roughness values are frequently observed especially at low cutting speeds in the processing of commercial purity materials such as aluminum, copper and nickel [26-29]. In almost all machining processes, it is expected that surface roughness values will decrease especially with increasing cutting speed [27-32].

Table 3. Ra, DD and CD which measured in experiments

Test no	Code	Vc (m/min)	Code	f (mm/rev)	Code	β (°)	Code	Coating condition	Ra (µm)	DD (mm)	CD (mm)
1	A1	10	B1	0.025	C1	90	D1	Uncoated	2.490*	0.035	0.041
2	A1	10	B2	0.050	C2	105	D1	Uncoated	2.959	0.051	0.058
3	A1	10	B3	0.075	C3	118	D2	Coated	3.103	0.018	0.023
4	A1	10	B4	0.100	C4	140	D2	Coated	3.436	0.027	0.032
5	A2	20	B1	0.025	C2	105	D2	Coated	2.714	0.015*	0.020*
6	A2	20	B2	0.050	C1	90	D2	Coated	2.513	0.023	0.028
7	A2	20	B3	0.075	C4	140	D1	Uncoated	4.099	0.042	0.048
8	A2	20	B4	0.100	C3	118	D1	Uncoated	3.978	0.051	0.057
9	A3	30	B1	0.025	C3	118	D1	Uncoated	2.582	0.019	0.025
10	A3	30	B2	0.050	C4	140	D1	Uncoated	2.784	0.024	0.030
11	A3	30	B3	0.075	C1	90	D2	Coated	3.394	0.035	0.041
12	A3	30	B4	0.100	C2	105	D2	Coated	3.728	0.049	0.056
13	A4	40	B1	0.025	C4	140	D2	Coated	2.637	0.019	0.024
14	A4	40	B2	0.050	C3	118	D2	Coated	3.031	0.026	0.031
15	A4	40	B3	0.075	C2	105	D1	Uncoated	3.603	0.037	0.043
16	A4	40	B4	0.100	C1	90	D1	Uncoated	4.178**	0.053**	0.060**
								Avarage	3.202	0.033	0.039

* minimal value, ** maximum value

3.1 Regression Analysis and Interaction of Control Factors

The regression equations required to calculate the variable values, (Ra, DD and CD) are given in Equation 3.1, Equation 3.2 and Equation 3.3, respectively. In equality; A is cutting speed, B is feed rate, C is drill bit angle and D is coating condition (Table 2 and Table 3).
It is desirable that the variables subject to experiments are at the lowest possible levels in drilling experiments. Therefore, while the increasing values of the variables in the negative factor state in the regression equations

obtained will have positive results, the decreasing values will have a negative effect.

Ra=2.22+0.0892A+0.440B+0.0207C–0.264D (3.1)
DD=0.0424+0.00020A+0.00699B–0.00353C–0.0125D (3.2)
CD=0.0488+0.00021A+0.00734B–0.00370C–0.0132D (3.3)

Table 4 gives the table of coefficients found after obtaining the regression equation. In this table; Coef: coefficients of values, SE Coef: standard error in coefficients, T: the result of test statistics, and P: whether regression analysis is significant indicates. The P values less than 0.05 is a proof that the control factor is statistically significant.

According to the regression equation (Equation 3.1) obtained for the average surface roughness, the highest coefficient belongs to the feed rate, followed by the coating condition, cutting speed and drill bit angle, respectively. When the P values in Table 4 are examined, it can be seen that the feed rate on the surface roughness is statistically significant. According to the regression equation (Equation 3.2) obtained for deviation from diameter, the highest coefficient belongs to the coating condition, followed by the feed rate, drill bit angle and cutting speed, respectively. When the P values in Table 4 are analyzed, it is seen that the feed rate and the coating condition on the deviation from diameter is statistically significant. According to the regression equation (Equation 3.3) obtained for deviation from cylindrical, the highest coefficient belongs to the coating state, followed by the feed rate, the drill bit angle and the cutting speed, respectively. When the P values in Table 4 are analyzed, it is seen that the feed rate and the coating condition are statistically significant on the deviation from cylindrical. When the determination coefficients (R^2) in Table 4 are examined, the test results of the regression equations obtained; we can explain it as 85.0% for surface roughness and 71.9% for deviation from diameter and cylindrical. In other words, a relative relationship can be mentioned between the variables.
Variance analyses of the multiple linear regression equation that we obtained in Table 5 are given. According to this table, P values are less than 0.05 and therefore we can say that we have statistically significant regression equations.

Table 4. Coefficients table of regression equations

	Term	Constant	Cutting speed	Feed rate	Drill bit angle	Coating condition	R-Sq (R^2)	R-Sq (adj) (R^2 adj)
Ra	Coef	2.2234	0.08922	0.44005	0.02074	-0.2645	85.0%	79.5%
	SE Coef	0.3292	0.05890	0.05890	0.05890	0.1317		
	T	6.75	1.51	7.47	0.35	-2.01		
	P	0.000	0.158	0.000	0.731	0.070		
DD	Coef	0.04236	0.000204	0.006987	-0.003527	-0.012547	71.9%	61.7%
	SE Coef	0.01015	0.001815	0.001815	0.001815	0.004059		
	T	4.17	0.11	3.85	-1.94	-3.09		
	P	0.002	0.912	0.003	0.078	0.010		
CD	Coef	0.4882	0.000215	0.007336	-0.003703	-0.013175	71.9%	61.7%
	SE Coef	0.01065	0.001906	0.001906	0.001906	0.004262		
	T	4.58	0.11	3.85	-1.94	-3.09		
	P	0.001	0.912	0.003	0.078	0.010		

Table 5. Variance analysis of regression equations

	Source	DF	SS	MS	F ratio	P value
Ra	Regression	4	6.2187	1.5547	19.71	0.000
	Error	11	0.8676	0.0789		
	Total	15	7.0863			
DD	Source	DF	SS	MS	F ratio	P value
	Regression	4	0.00224534	0.00056134	7.04	0.005
	Error	11	0.00087714	0.00007974		
	Total	15	0.00312248			
CD	Source	DF	SS	MS	F ratio	P value
	Regression	4	0.00170900	0.00042725	19.35	0.000
	Error	11	0.00024294	0.00002209		
	Total	15	0.00195194			

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3.2 Tool Wear and Deviation from Tolerances

When Figure 3 is examined, it is seen that the surface roughness values measured as a result of drilling of commercial grade copper material are affected by the changes in the feed rate. The increase in the feed rate has a negative effect on the surface roughness. The increase in cutting speed does not affect the surface roughness much. In addition, when the drill bits pictures in Figure 4 are examined, it is seen that the workpiece material tends to stick on the cutting tool, especially at low cutting speed and high feed rates. It is thought that the high surface roughness is due to the effect of adhesion on the cutting tool.

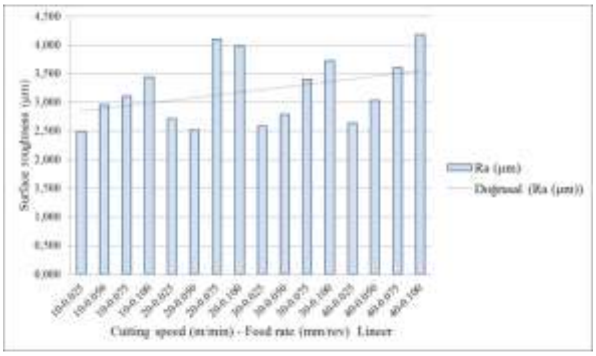

Figure 3. Average surface roughness values

Figure 4. Used drill bit in experiments

According to the regression analysis, it was stated that the surface roughness value was most affected by the coating condition. In Figure 4, it is seen that in uncoated cutting tools, adhesion is more effective than coated tools. Almost all uncoated cutting tools have adhesion marks on the chisel edge.

When looking at the graphs in Figure 5, it can be said that changes in cutting speed and feed rates have a similar effect on deviation from diameter and deviation from cylindrical. In particular, deviation values were significantly affected due to the increase in the amount of progress, and deviation amounts increased. It can be said that work pieces sticking to chisel edge are effective on deviation values from diameter and cylindrical.

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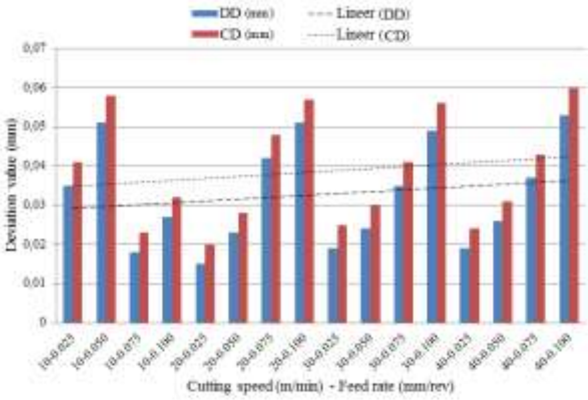

Figure 5. Deviation values from diameter and cylindrical

3.3 Burr Formation

Residual workpiece materials (burrs) remaining on the machined material after machining significantly affect workpiece quality and machining efficiency. These burrs should be removed with a second process and this process will be a negative effect increasing costs. For this reason, burr formation should be either prevented completely or kept as low as possible. In Figure 6, images of the entrance and exiting parts of the holes formed as a result of the experiment are given. It is seen that the burrs formed in the entrance part of the holes are quite less than the burrs formed in the exiting part.

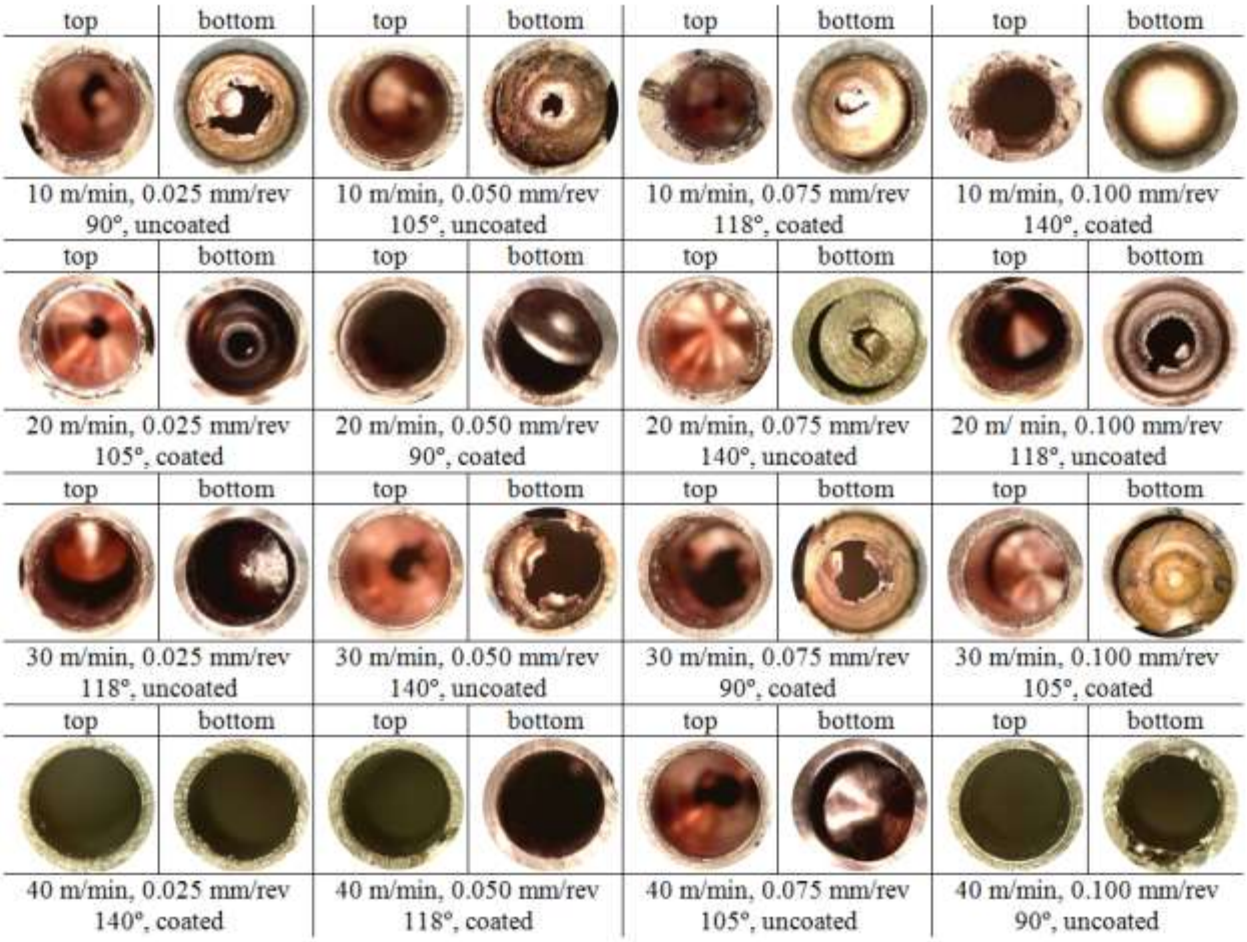

Figure 6. Top and bottom views of holes (entrance and exiting of the holes)

When Figure 6 is examined, it is seen that the burrs formed at the entrance are affected by the changes in cutting speed and feed rate. Despite the increased cutting speeds, the entrance parts of the holes are smoother with low feed rate. Also, a clear circularity is observed in the holes obtained with coated drill bits at 30 and 40 m/min cutting speeds.

Very high burr formation is observed at the exiting parts of the drilled holes. This is thought to be due to the high elasticity value of copper. It is seen that the burring formed in the exiting part decreases relatively with increasing cutting speed and decreasing the feed rate. In addition, it is observed that burr formation decreases in coated drill bits compared to uncoated drill bits. The reason for this can be explained by the fact that the coating has a significant effect on the cutting tool, making the chip more comfortable and easily removing the chip. In Figure 6, top is entrance of the holes and bottom is exiting of the holes.

4. Conclusion

In this study, the surface roughness, deviation from diameter and deviation from cylindrical obtained by drilling commercial purity copper material with HSS cutting tools using 4 different variables (cutting speed, feed rate, drill bit angle and coating condition) were investigated. Also, tool wear and burr formation occurring as results of the experiment were evaluated according to variable drilling parameters. As results of the study, the following results were obtained.

- As a result of the regression analysis, it was observed that the feed rate was effective on the surface roughness and the deviation from the cylindrical, and also the coating condition was significantly influenced on the results for the deviation from the diameter.

- It has been observed that the surface quality increases with increasing cutting speeds and low feed rates.

- It has been found that the holes obtained with coated drill bits have lower surface roughness values and deviations of the geometric have lower values.

- The burr formations at the entrance of the holes are very small, but coated drill bits at higher machining speeds gave better results.

- It was observed that burr formation, increased at high feed rate values at the exiting of the holes and decreased at high cutting speeds.

- Intense burr formation was observed at the exiting of the holes and in cases where the burr thickness was high (at high feed values), the quality of the hole was negatively affected.

- In almost all experiments, the adhesion of the workpiece material to the drill bit chisel angle has been observed. Increasing the cutting speed has decreased the sticking significantly.

- In the increasing values of the feed rate, the adhesion of the workpiece material on the drill bit has increased, and it has adversely affected the workpiece quality.

Author Contributions

Hüseyin GÖKÇE: Drafted and wrote the manuscript, performed the experiment and result analysis.

Ethics

There are no ethical issues after the publication of this manuscript.

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