Investigating the Effects of Drilling Parameters on Drill Bit Temperature in Drilling of Carbon Black Reinforced Polyamide using Taguchi Method

Alper Uysal, and Erhan Altan

***Abstract*—**Polymers have been used in various industries and can be produced by forming in the mold but machining operations are usually performed due to needing in the assembly and fixing processes. In particular, drilling of engineering plastics such as polyamide, polyethylene etc. have been investigated by scientists. Additionally, electrically conductive polymers have been developed by adding conductive materials like carbon black, carbon nanotube, graphene etc. to the polymer matrix for electronic applications and automotive industry. For these reasons, this study aims to investigate the effects of drill point angle, feed, and cutting speed on the drill bit temperature by Taguchi and ANOVA (analysis of variance) statistic methods in the drilling of unreinforced polyamide and carbon black reinforced electrically conductive polyamide. In addition, the relation between the drill bit temperature and burr was examined. The optimum drilling condition for minimum drill bit temperature was determined at low cutting speed and drill point angle and high feed for given drilling parameters. It was specified that the drill bit temperature was higher in the drilling of carbon black reinforced polyamide than that measured in the drilling of unreinforced polyamide. The most significant parameter was obtained as the drill point angle by Taguchi method and ANOVA results confirmed this result. Additionally, it was observed that burr formation increased as increasing the drill bit temperature.

***Keywords*—**Carbon black, drill bit temperature, electrically conductive polymer, polyamide

I. Introduction

POLYMERS and polymeric materials have attracted great interest from industrial and academic researches and they have been used in many applications from consumer products to high temperature industrial usage. Polyamide is one of the most preferred polyamides due to presenting a good compromise between toughness and strength, low friction coefficient, and high thermal resistance [1]. In the recent times, conductive polyamide composites produced by adding of conductive filler such as carbon black, carbon nanotubes, or graphene [2] have been investigated because of their potential applications in automotive and electronic industries. The polyamide products can be manufactured by injection molding but machining operations, in particular drilling process, are generally conducted for fixing and assembly. Some researchers examined the drilling of polymers and reinforced polymers. Endo and Marui [3] investigated the effects of spindle speed and feed on the radius error in the drilling of polyacetal (POM) and polyetherimide (PEI). Researchers indicated that the radius error increased when the feed was small and the spindle speed was large. Khashaba et al. [4], [5] investigated the effects of cutting speed, feed, and drill diameter on thrust force, drilled holes, and drill wear in the drilling of woven glass fiber reinforced epoxy composite. It was observed that the behavior of thrust force was affected by drill pre-wear and this effect was more significant at high cutting speed and feed. Rubio et al. [6] focused on the high speed drilling of 30% glass whisker reinforced polyamide composite and studied the effects of feed rate, spindle speed, and drill point angle on surface roughness. The lowest surface roughness was measured in the drilling at feed rate of 3000 mm/min and spindle speed of 8000 rpm. Gaitonde et al. [7] analyzed the effects of cutting speed and feed rate on surface roughness in the high speed drilling of unreinforced polyamide and 30% glass fiber reinforced polyamide. Surface roughness values of reinforced polyamide were obtained lower than that of unreinforced polyamide and the surface roughness decreased with increase of feed rate. Uysal et al. [8] investigated the effects of cutting speed, feed, and drill point angle on the drill wear by Taguchi method and ANOVA (analysis of variance) analysis in the drilling of sheet molding compound composite. The feed was found the important factor. Wang et al. [9] studied the wears of uncoated, diamond coated, and AlTiN (aluminum titanium nitride) coated carbide drills in the drilling of carbon fiber reinforced composite. In all types of drills, it was found that the main wear type was the edge rounding wear. Rubio et al. [10] examined the effects of spindle speed, feed, and drill point angle on the hole diameter, radial error, and thrust force in the drilling of polyamide and 30% glass whisker reinforced polyamide by Taguchi method. Depending on the researchers' study, the drill point angle was found as main drilling parameter. Rubio et al. [11] identified the effects of the feed, spindle speed, and drill point angle on the radial error, surface roughness, and thrust force in the drilling of ultra high molecular weight polyethylene

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(UHMWPE), polyoxymethylene (POM), and polytetrafluoroethylene (PTFE). The maximum radial error and surface roughness were measured in the drilling of UHMWPE and the minimum radial error was found at high feed and drill point angle and low spindle speed. Gaitonde et al. [12] experimentally studied the hole quality in the drilling of unreinforced polyamide and 30% glass fiber reinforced polyamide. In the given drilling conditions, the hole quality increased at high spindle speed, low feed and drill point angle for both polyamides. Altan and Altan [13] investigated the exit burr height in the drilling of UHMWPE by coated and uncoated HSS (high speed steel) twist drills. The effects of cutting speed, feed, and HSS tool type were determined by Taguchi method. According to the experimental results, the burr height decreased with increase of the feed and decrease of the cutting speed. Besides, uncoated HSS drill led to a reduction of the burr height.

In this study, the drill bit temperature was examined and the effects of drill point angle, feed, and cutting speed were determined by utilizing Taguchi method and ANOVA analysis during the drilling of unreinforced polyamide and carbon black reinforced electrically conductive polyamide. Additionally, the relation between drill bit temperature and burr was investigated.

II. Experimental Study

A. Materials and Equipments

In this study, unreinforced polyamide (PA) and carbon black reinforced electrically conductive polyamide (CBR-PA) were chosen as workpiece materials. Technical properties of unreinforced polyamide (Eurotec®) and carbon black reinforced polyamide (Premix PRE-ELEC® PA 1411) specimens are given in Table I.

TABLE I
Technical Properties of Unreinforced and Carbon Black Reinforced Polyamides

Properties	Unreinforced Polyamide	Carbon Black Reinforced Polyamide
Specific gravity	1,14 gr/cm^3	1,25 gr/cm^3
Yield strength	76 MPa	70 MPa
Flexural modulus	3250 MPa	3100 MPa
Elongation at break	≥50%	12%
Elongation at yield	12%	8%
Volume resistivity	≥10^{14} Ωcm	<50 Ωcm
Surface resistance	>10^{13} Ω	<10^4 Ω

Unreinforced and carbon black reinforced electrically conductive polyamide granules were dried at 60°C for 2 hours. After that polyamide specimens were produced by injection molding in dimensions of 150x150x10 mm. During the plastic injection process, the polyamide granules were melted at 220°C, the mold temperature was set at 60ºC and injection pressure was applied by 70 MPa. Drilling operations were performed at First MCV-300 CNC machining center by using uncoated HSS (High Speed Steel) twist drill tools in diameter of 8 mm.

Drill bit temperatures (T) were measured by Optris® CTlaser LT two-wire infrared thermometer which measurement range is -50°C to 975°C with ±1% measurement accuracy and response time is 9 ms. Temperature measurements were performed just after the drilling tool exited from the drilled hole. The burrs were photographed by SOIF XLB45-B3 digital stereo microscope.

B. Design of the Experiments

Taguchi experimental design method and analysis of variance (ANOVA) statistic method were utilized to determine the optimum drilling parameters and to specify the effects of drilling parameters on the drill bit temperature. Drill point angle, feed, and cutting speed were selected as key factors and levels can be seen in Table II.

TABLE II
Variable Factor Levels

Factors	Level 1	Level 2
Drill Point Angle (α), A [°]	80	120
Feed (f), B [mm/rev]	0,1	0,3
Cutting Speed (V), C [m/min]	40	120

In this study, Taguchi L_8 was chosen and the layout of the L_8 is given in Table III. The signal-to-noise (S/N) ratio was calculated to specify the quality characteristic and the S/N ratios were determined by

$$S/N = -10\log\left[\frac{1}{n}\cdot\sum_{i=1}^{n} y_i^{\,2}\right] \qquad (1)$$

In equation (1), n is the number of data sets and y_i is the measured value for the i_{th} data set.

TABLE III
The Layout of Taguchi L_8

Experiment Number	Drill Point Angle A	Feed B	Cutting Speed C
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2

In addition, the multivariable linear regression analyses were employed for unreinforced and carbon black reinforced polyamides to determine the correlations between the factors and the drill bit temperatures. In this study, the statistical analyses were carried out by using Minitab® statistical software.

III. Analyses of the Results

A. The Effects of Drilling Parameters on the Drill Bit Temperature

In the drilling of unreinforced and carbon fiber reinforced electrically conductive polyamides, the variations of drill bit temperature according to the drill point angle, feed, and cutting speed are given in Fig. 1. Depending on the experimental results, it was observed that the drill bit temperature decreased with decrease of drill point angle because of the fact that the small drill point angle made easier the cutting of polymer than the large drill point angle. Besides, the drill bit temperature decreased as decreasing the cutting speed and increasing the feed due to increasing the friction between drill tool and polyamide. In general, the carbon black reinforcement is added to the polymers to improve the electrical conductivity but this reinforcement improves the thermal conductivity as well as the electrical conductivity and makes the polymer tougher. In addition, it is known that the heat accumulates on the polymer surface in machining of polymers due to the lack of thermal conductivity. For these reasons, carbon black reinforced polyamide conducted more heat to the drill tool than unreinforced polyamide and so more drill bit temperatures were measured.

B. Taguchi Method

Taguchi method was performed to specify the optimum drilling parameters for minimum drill bit temperature. The measured drill bit temperatures and the corresponding signal-to-noise (*S/N*) results for unreinforced and carbon black reinforced polyamides can be seen in Table IV and Table V, respectively. In this study, “smaller is better” quality characteristic was selected to calculate the *S/N* ratios. The response tables of the *S/N* ratios for unreinforced and carbon black reinforced polyamides are given in Table VI and Table VII, respectively. The best combination set of the factors is determined by selecting the highest levels of the factors from Table VI and Table VII. Consequently, the optimum drilling parameters were determined as A1, B2, C1 for both polyamides. According to the delta values, the most effective parameter on the drill bit temperature was drill point angle for both unreinforced and carbon black reinforced polyamides with the delta value of 1,88 and 2,06, respectively. Additionally, the least effective factor was found as feed with the lowest delta value of 1,18 for both polyamides.

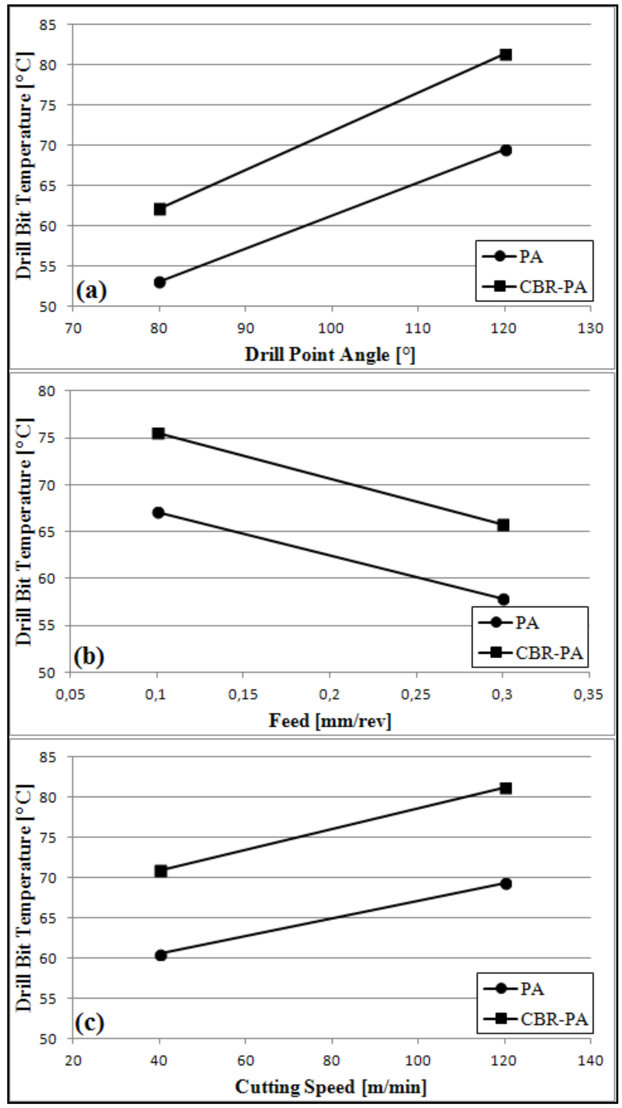

Fig. 1 The influence of drilling parameter on the drill bit temperature a) *f*= 0,1 mm/rev, *V*= 40 m/min, b) *α*= 80°, *V*= 120 m/min, c) *α*= 120°, *f*= 0,3 mm/rev

TABLE IV
EXPERIMENTAL RESULTS AND S/N RATIOS FOR UNREINFORCED POLYAMIDE

Exp. Nu.	Drill Point Angle [°]	Feed [mm/rev]	Cutting Speed [m/min]	Drill Bit Temperature [°C]	S/N [dB]
1	80	0,1	40	53,1	-34,502
2	80	0,1	120	67,1	-36,534
3	80	0,3	40	48,5	-33,715
4	80	0,3	120	57,9	-35,254
5	120	0,1	40	69,5	-36,840
6	120	0,1	120	81,8	-38,255
7	120	0,3	40	60,5	-35,635
8	120	0,3	120	69,3	-36,815

TABLE V
EXPERIMENTAL RESULTS AND S/N RATIOS FOR CARBON BLACK REINFORCED POLYAMIDE

Exp. Nu.	Drill Point Angle [°]	Feed [mm/rev]	Cutting Speed [m/min]	Drill Bit Temperature [°C]	S/N [dB]
1	80	0,1	40	62,20	-35,876
2	80	0,1	120	75,57	-37,567
3	80	0,3	40	56,79	-35,085
4	80	0,3	120	65,79	-36,363
5	120	0,1	40	81,38	-38,210
6	120	0,1	120	96,78	-39,716
7	120	0,3	40	70,84	-37,006
8	120	0,3	120	81,14	-38,185

TABLE VI
THE RESPONSE TABLE OF S/N RATIOS FOR UNREINFORCED POLYAMIDE

	Drill Point Angle [°]	Feed [mm/rev]	Cutting Speed [m/min]
Level 1	-35,00	-36,53	-35,17
Level 2	-36,89	-35,35	-36,71
Delta	1,88	1,18	1,54

Fig. 2 and Fig. 3 represent the *S/N* ratio graphs of unreinforced polyamide and carbon black reinforced polyamide, respectively. The highest S/N ratio of each drilling parameter presented the optimum drilling conditions and for both polyamides, they corresponded to the drill point angle of 80°, the feed of 0,3 mm/rev, and the cutting speed of 40 m/min. This data set was in the experimental design (experiment number of 3) and the measured drill bit temperatures were 48,5°C with *S/N* ratio of -33,715 and 56,79 with *S/N* ratio of -35,085 for unreinforced polyamide and carbon black reinforced polyamide, respectively.

TABLE VII
THE RESPONSE TABLE OF S/N RATIOS FOR CARBON BLACK REINFORCED POLYAMIDE

	Drill Point Angle [°]	Feed [mm/rev]	Cutting Speed [m/min]
Level 1	-36,22	-37,84	-36,54
Level 2	-38,28	-36,66	-37,96
Delta	2,06	1,18	1,41

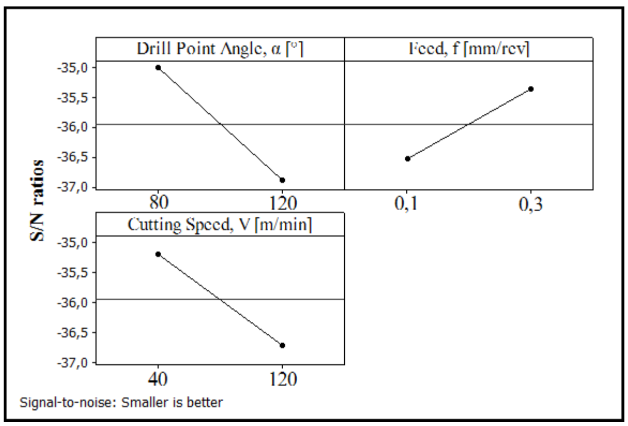

Fig. 2 S/N ratios of unreinforced polyamide for drill bit temperature

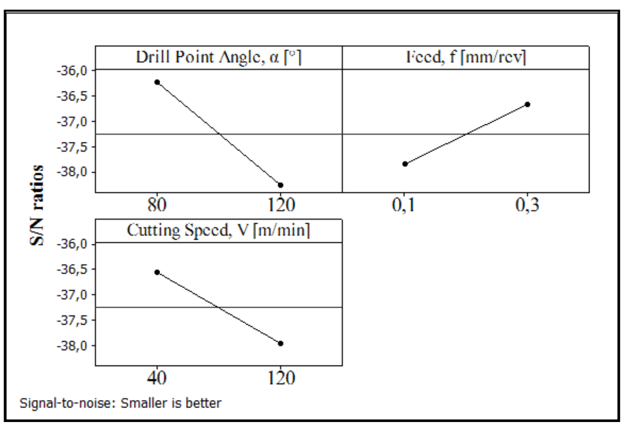

Fig. 3 S/N ratios of carbon black reinforced polyamide for drill bit temperature

C. Analysis of Variance (ANOVA)

Drill point angle was found as the most significant drilling parameter for minimum drill bit temperature by Taguchi method. As given in Table VIII and Table IX, ANOVA statistic results verified this result for both polyamides. In the drilling of unreinforced polyamide, the contribution ratios of drill point angle, cutting speed, and feed were calculated as 46,94%, 31,29%, and 19,69%, respectively. During the drilling of carbon black reinforced, the contribution ratio of drill point angle was found as 53,44% followed by cutting speed with the value of 25,35%. These results are compatible with the results obtained from Taguchi method.

TABLE VIII
ANOVA RESULTS FOR UNREINFORCED POLYAMIDE

Parameter	Sum of square	Degree of freedom	Mean square	F-ratio	Cont. ratio [%]
Drill Point Angle	371,28	1	371,28	90,4	46,94
Feed	155,76	1	155,76	37,9	19,69
Cutting Speed	247,53	1	247,53	60,3	31,29
Error	16,42	4	4,11		
Total	791	7			

TABLE IX
ANOVA RESULTS FOR CARBON BLACK REINFORCED POLYAMIDE

Parameter	Sum of square	Degree of freedom	Mean square	F-ratio	Cont. ratio [%]
Drill Point Angle	608,83	1	608,83	87,4	53,44
Feed	213,93	1	213,93	30,8	18,78
Cutting Speed	288,84	1	288,84	41,6	25,35
Error	27,76	4	6,94		
Total	1139,37	7			

D. Multivariable Linear Regression Analysis

The correlations between drilling parameters and drill bit temperature were determined by multivariable linear regression analysis and the results can be seen in Table X and Table XI for unreinforced polyamide and carbon black reinforced polyamide, respectively. Besides, models can be seen in equation (2) and equation (3). The R^2 values were calculated as 97,92% and 97,56% for unreinforced and carbon black reinforced polyamides, respectively. This means that the models are acceptable to predict the drill bit temperature for given drilling conditions.

TABLE X
MULTIVARIABLE LINEAR REGRESSION ANALYSIS FOR DRILL BIT TEMPERATURE IN THE DRILLING OF UNREINFORCED POLYAMIDE

Parameter	Coefficient	Standard error	T-statistics	P-value
Constant	27,1	4,17751	6,48712	0,003
Drill Point Angle	0,3406	0,03582	9,50887	0,001
Feed	-44,125	7,16436	-6,15895	0,004
Cutting Speed	0,1391	0,01791	7,76412	0,001

$$T_{PA} = 27{,}1 + 0{,}3406.\alpha - 44{,}125.f + 0{,}1391.V \qquad (2)$$
$$R^2 = 0{,}9792$$

TABLE XI
MULTIVARIABLE LINEAR REGRESSION ANALYSIS FOR DRILL BIT TEMPERATURE IN THE DRILLING OF CARBON BLACK REINFORCED POLYAMIDE

Parameter	Coefficient	Standard error	T-statistics	P-value
Constant	28,5175	5,43096	5,25091	0,006
Drill Point Angle	0,4362	0,04657	9,36625	0,001
Feed	-51,7125	9,31403	-5,55211	0,005
Cutting Speed	0,1502	0,02329	6,45129	0,003

$$T_{CBR-PA} = 28{,}5175 + 0{,}4362.\alpha - 51{,}7125.f + 0{,}1502.V \quad (3)$$
$$R^2 = 0{,}9756$$

The predictive validity (Δ) of the both models can be determined by equation (4). In equation (4), P is for the predicted drill bit temperature from the models and E is for the experimental drill bit temperature.

$$\Delta = \frac{|P - E|}{E}.100 \quad (4)$$

The average error of the model for drilling of unreinforced polyamide was calculated as 1,874% and that for drilling of carbon black reinforced polyamide was found as 2,067%. The approximation graphs of the drill bit temperature models are given in Fig. 4 and Fig. 5 for unreinforced and carbon black reinforced polyamides, respectively.

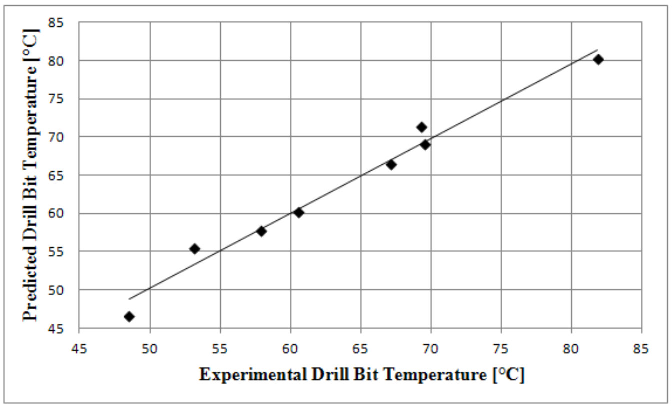

Fig. 4 The approximation of the model for unreinforced polyamide

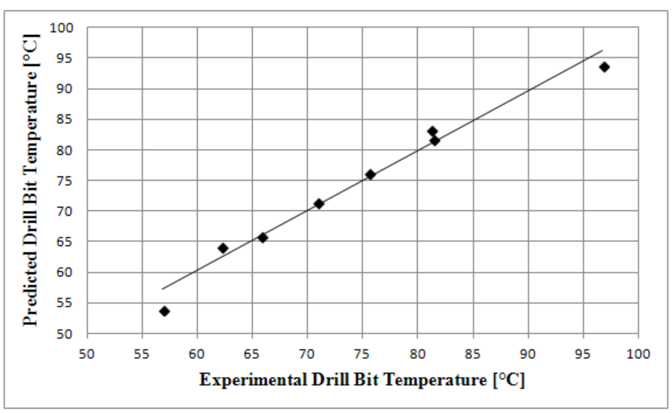

Fig. 5 The approximation of the model for carbon black reinforced polyamide

In table X and Table XI, all P-values were determined less than 0,01 and this means that all drilling parameters in the models are statistically significant at the 99% confidence level. For both models, the drill point angle was found as the most effective variable with the smallest P-values and the feed was found as the least effective variable with the highest P-values. These results are compatible with the results of Taguchi method and ANOVA analysis.

E. Relation between Drill Bit Temperature and Burr

Fig. 6 and Fig. 7 represent the relation between the drill bit temperature and the burr for unreinforced polyamide and carbon black reinforced polyamide, respectively. Higher drill bit temperature caused much more burr due to the fact that the high temperature made the polyamide softened and it could not be cut efficiently. It was observed that the unreinforced polyamide was more affected from the heat than the carbon black reinforced polyamide and more burrs were formed in the drilling of unreinforced polyamide. In addition, more favorable holes were obtained in the drilling of carbon black reinforced polyamide because of being tougher than the unreinforced polyamide.

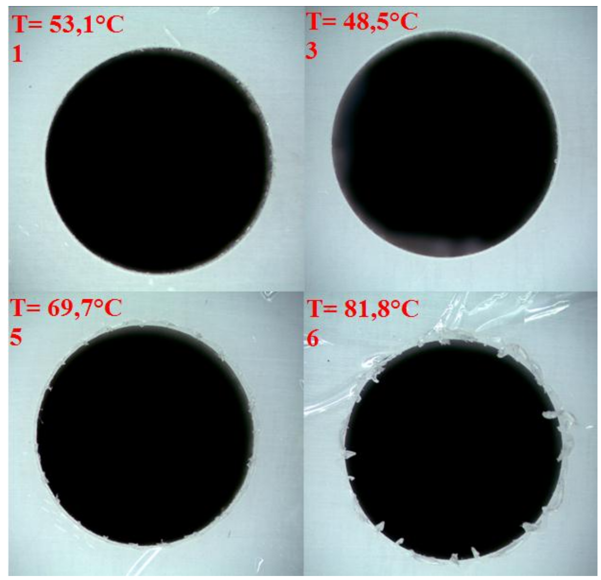

Fig. 6 The relation between drill bit temperature and burr for unreinforced polyamide

IV. Conclusion

In this study, the effects of drill point angle, feed, and cutting speed on the drill bit temperature were investigated in the drilling of unreinforced polyamide and carbon black reinforced electrically conductive polyamide. For this reason, Taguchi method and ANOVA statistic method were utilized and multivariable linear regression models were established. In addition, the relation between drill bit temperature and burr was observed. Depending on the experimental and statistical results, below points were obtained:

- Drill bit temperature increased with increase of the drill point angle and the cutting speed and with decrease of the feed.
- In the drilling of carbon black reinforced polyamide, more drill bit temperatures were obtained than that occurred in the drilling of unreinforced polyamide.
- The optimum drilling parameters were determined as the drill point angle of 80°, the feed of 0,3 mm/rev, and the cutting speed of 40 m/min by utilizing Taguchi method for both polyamides.
- The most effective parameter was determined as the drill point angle by Taguchi method and ANOVA for both polyamides. The least effective factor was found as the feed.
- According to the drilling parameters, the drill bit temperature models were established by multivariable linear

regression analysis. The average errors of the models were found as 1,874% and 2,067% for unreinforced polyamide and carbon black reinforced polyamide, respectively.

- For a given polymer, more burrs were observed, when the drill bit temperature increased. Additionally, drilled holes on the unreinforced polyamide were much affected by the heat in comparison to the carbon black reinforced polyamide.

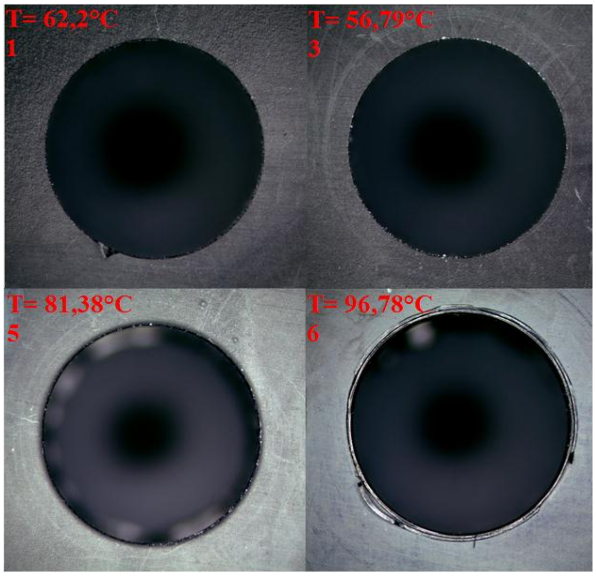

Fig. 7 The relation between drill bit temperature and burr for carbon black reinforced polyamide

ACKNOWLEDGMENT

This research has been supported by Yıldız Technical University Scientific Research Projects Coordination Department. Project Number: 2014-06-01-GEP01.

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