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ORIGINAL ARTICLE

Influence of different cooling methods on drill temperature in drilling GFRP

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Abstract Drilling of composite materials is difficult to carry out due to their anisotropic and non-homogenous structure and the high abrasiveness of their reinforced constituent. This results in high temperature during drilling, leading to rapid wear development in the cutting tool. The present work investigates the drilling of glass fibre-reinforced polymer composites with TiN/TiAlN-coated carbide drills on a computer numerical control (CNC) lathe for different cooling conditions. The objective of this work is to study the influence of different cooling conditions on drill bit temperature and drill bit wear. The signal to noise (S/N) ratio and analysis of variance (ANOVA) were employed to analyse the effect of cooling condition on drilling parameters. A linear polynomial model was developed using multiple regression analysis between drilling parameters and cooling condition with the drill bit temperature to represent the fitness characteristics. The workpiece made of GFRP is machined, and temperature is monitored during dry drilling, internal coolant and external coolant. The temperature of drill bit was measured by PFA Teflon-coated K (Chromega-Alomega) type thermocouples. From the analysis, it is evident that a linear multiple regression models developed to relate the cutting temperature with drilling parameters are with a minimum error of ±7 %. Internal coolant method reduces the average temperature by 76 % compared with dry drilling and 66 % compared with external coolant method. The reduction in tool temperature reduces the flank wear and increases the tool life by 43.75 % compared with dry drilling and 25 % compared with external coolant method.

Keywords Drill bit temperature · Flank wear · Tool life

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1 Introduction

The most recent development of high-performance fibres has led to the availability of composites which can compete and indeed replace metals. Glass fibre-reinforced composites are perhaps the most commonly used ranging in application from helmets, fishing boats, automobile body and aircraft structures due to their lightweight, high modulus and specific strength. As structural materials, holes are to be produced in large number for fastening and assembly. Due to continuous drilling, the high temperature on drill bit edges produces thermal cracking, fracturing of the cutting edges, plastic deformation of cutting edges and rapid tool wear which reduces tool life. The magnitudes of the cutting temperatures need to be known to facilitate assessment of machinability and tool life and to evaluate the variation of machining parameters. Also, drilling parameters can only be increased if effective cooling of the cutting edge could contain temperatures. Coolant system will facilitate chip evacuation, removing of heat and ensure good machined surface quality. Since the drill bit cost is high compared to coolant cost on all CNC machines, we use different coolant system to distribute precise amount of coolant at the interface between cutting edge and workpiece externally and internally.

Machining of composites differs significantly from machining conventional metals and alloys, owing to the behaviour of matrix material, reinforcement, diverse properties of fibre, orientation of fibre and volume fraction of fibres [1]. A few researchers carried out experimental investigations to analyse the machining characteristics of GFRP by drilling or turning.

Agapiou and Devires [2] have analytically calculated the temperature distribution of twist drills on the flank face and cutting edge to explain thermal phenomena during the cutting process. On the other hand, Agapiou and Stephenson [3] have made a model for calculating transient and steady-state drill temperatures with arbitrary geometries. They have used thermocouple and thin wire thermo-junction in their study.

Rivero et al. [4] investigated the effect of coatings and cutting parameters on the drilling temperatures for dry drilling of aluminium alloys. In their work, the drilling temperature was measured using thermocouples and the infrared pyrometer technique. Dorr et al. [5] have studied the temperature during the drilling process including the effect of the different tool coatings. Kalidas S et al. [6] investigated the thermal expansion of drills under dry and wet drilling conditions. Komanduri and Hou [7], Tay [8] and Da Silva and Wallbank [9] reviewed the methods to measure the temperature between cutting tool and workpiece as well as cutting tool and chip.

Bagci and Ozcelik [10] have experimentally measured the drill bit temperature to study thermal phenomena during the dry drilling of aluminium and steel and compared with FEA results. Fuh and Liang [11] analysed the temperature distribution on the conventional drill during the cutting process by means of 3D FEM. In their study, the effects of depth of cut, cutting speed, web thickness and helix angle of drill bit on the temperature changes are investigated.

Malhotra [12] reported the occurrence of both chisel edge and flank wear during drilling of carbon epoxy composite laminate with High Speed Steel (HSS) and carbide drills at a relatively low spindle speed of 1,250 rpm and feed rate of 60 μm/rev. Carbide drills were found to perform better than HSS tools.

Hasegawa [13] tool wear increases with increase of cutting speed and vice versa. The higher cutting speed was found to cause large deformation rate of glass fibre and severe tool wear.

Inoue et al. [14] investigated the influence of tool wear on the internal damage in small diameter drilling of glass fibre epoxy composites. They found higher flank wear to occur at lower feed rates and higher cutting speed.

Lin and Chen [15] compared the performance of standard twist drill and multifaceted drills in ultra-high-speed drilling (up to 38,000 rpm) of carbon fibre-reinforced poymer (CFRP) composites and found aggressive tool wear to be a major problem at such speeds. They observed that the increase in tool wear to be a major problem at such speeds. They observed that the increase in tool wear is associated with the increase in thrust and tangential forces.

Kim and Ramulu [16] performed an evaluation of HSS and carbide tools in drilling graphite fibre bismalimide (Gr/Bi) composite and titanium alloy stacks. Carbides, having higher hot hardness, were found to outperform HSS. The flank wear was found to increase both with spindle speed and feed rate. Murphy et al. [17] tested the performance of coated and uncoated tungsten carbide drills in drilling carbon fibre epoxy composites at spindle speed of 3,000 rpm and feed rate of 50 μm/rev. The effect of the increase in the flank wear on the cutting force, torque and the damage to the CFRP composite material was studied.

Sanjay Rawata and Helmi Attia [18] used a system-based approach for high-speed drilling (10,000–15,000 rpm) of woven graphite epoxy composites to investigate various tool wear mechanisms of carbide tools and their affect on the hole quality.

Glass fibre exhibits higher resistance to cutting, and hence, GFRP requires polycrystalline diamond and carbide tools. Due to the higher cost and the associated equipment required, diamond tooling is not often recommended. Carbide tools give a better finish of acceptable level at a lower cost.

It is well-known fact that high temperatures in modern metal cutting are the cause of unsatisfactory cutting tool life and limitation on cutting speed. Therefore, the most suitable drilling parameters have to be selected. One of the important factors of tool life is tool wear and is thought to be closely related to the temperature existing at the wearing surfaces of the tool. A complete tool temperature field is prerequisite for studying the basic tool wear. Very few authors have discussed about drilling of composite materials by using internal coolant method due to the problem in location of thermocouple for predicting temperature exactly at the cutting zone; hence, experimental investigation is carried out to determine the influence of different cooling methods in drill temperature and flank wear in drill bit during drilling glass fibre-reinforced composite with tungsten carbide-coated drill.

2 Experimental set-up

The drilling experiments involved dry drilling and drilling with coolant (external and internal) with a MATECH computer numerical control (CNC) lathe. Figures 1 and 2 show the schematic representation and photographic view of the experimental set-up. Drill temperatures were measured using a thermocouple with data acquisition card during the experiments. The depth of the hole was kept constant at 20mm during the entire investigation.

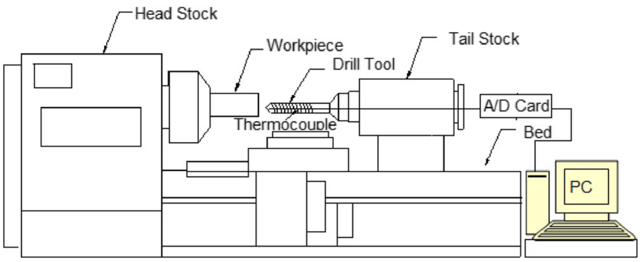


Fig. 1 Schematic representation of experimental set-up

2.1 Cutting tools and workpiece material

The coated carbide drilling tool with the code of Coro Drill Delta-C R846 that was utilized in drilling GFRP composite was selected from the Sandvik Coromant catalogue as shown in Fig. 3. The dimensional properties of the drilling tool are displayed in Table 1. Six TiN/TiAlN-coated carbide drills with diameter of 10 mm tools were used in total, with each drill being used four to five times.

In this experiment, the GFRP samples with diameter of 25 mm and length of 20 mm prepared through hand lay-up technique and used as workpiece. High-strength E glass fibre was used as reinforcement in epoxy resin to prepare hand lay-up rods with araldite as hardener. The prepared workpiece is an E glass/epoxy-woven fabric with a fibre volume fraction of 40 % with a young's modulus 32 GPa and a tensile strength of 60 MPa.

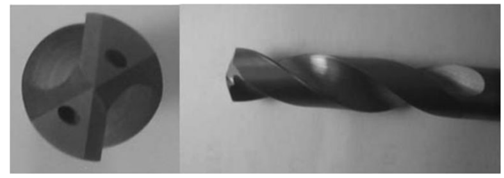


Fig. 3 The drilling tool with the code of Coro Drill Delta-C R846

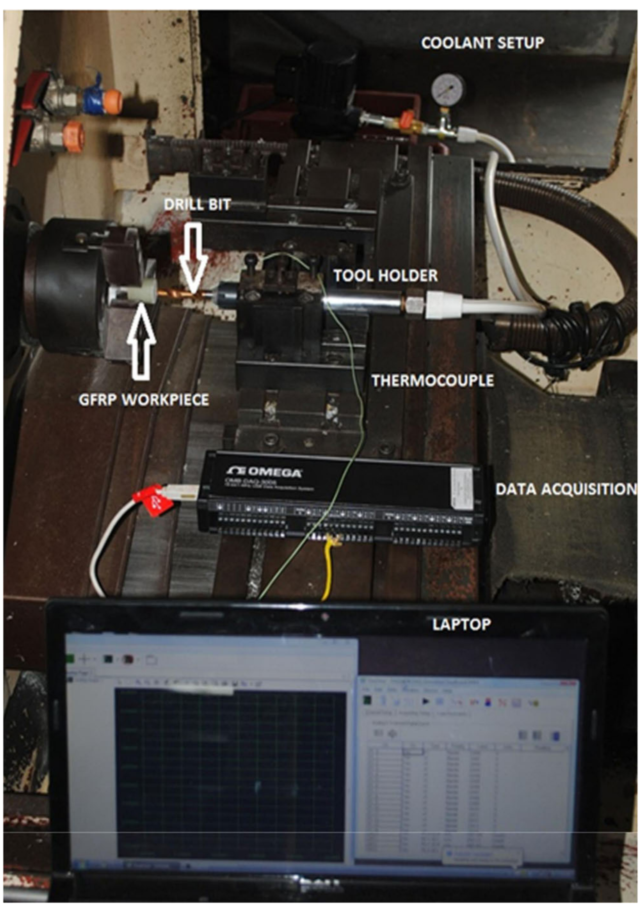


Fig. 2 CNC lathe and temperature measurement set-up used in the experiment

2.2 Temperature measurement

In this study, drill temperature was measured with a PFA Teflon-coated K (Chromega-Alomega) type thermocouples with a diameter of 127 μm. The range of thermocouple is 0–500 °C, and its response time is 10 μs. The thermocouple was inserted through the coolant hole and positioned near the tip drill bit as shown in Fig. 4. Then, the drill bit is put into a specially designed fixture and fixed on the tool post of the lathe. OMB-PDQ30 analogue input expansion module with sampling rate of 1 MHZ is connected with thermocouple output and interfaced with computer for investigation.

2.3 Flank wear measurement

Tool wear is the dominant phenomenon that affects tool life. The most important types of wear in drilling are flank wear. Flank wear produces wear lands on the side and end flanks of the tool because of the rubbing action of the machined surface, which has been considered in this work and measured by using a tool maker's microscope.

2.4 Plan of experiments

The methodology of Taguchi for three factors at three levels was used for the implementation of the plan of experiments as shown in Table 2. The orthogonal array selected was L9 (3^3) as shown in Table 3. A total of nine experiments were carried out considering speed, feed and coolant pressure for drilling

Table 1 Dimensional properties of the drilling tool

Dimensional properties	Value
Tool diameter	10 mm
Flute	2 flute
Tool overhang	47 mm
Point angle	140°
Helix angle	30°
Shank type	Cylindrical
Coating (multi layers)	TiN/TiAlN
Coating thickness	6 μm

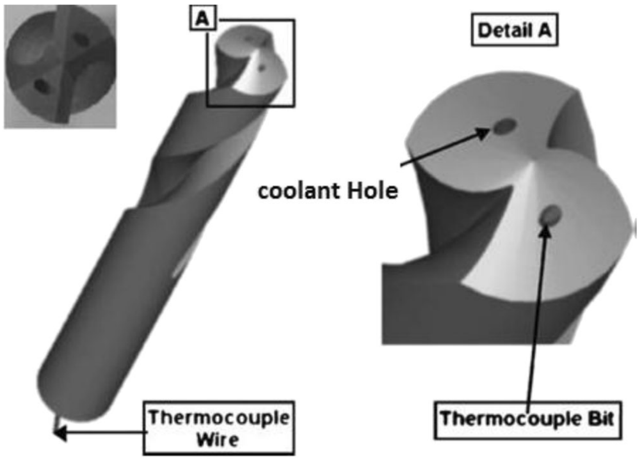


Fig. 4 The thermocouple inserted through the coolant hole of internal coolant carbide drill

with internal and external coolant and speed, feed for dry drilling. Each experiment has been repeated for three times for different coolant method, and the temperature is recorded for 30 s.

3 Experimental observation

The average maximum temperature against machining time for different cooling conditions is shown in Fig. 5.

3.1 Dry drilling

Typical temperature monitored during dry drilling for 30 s for the experiment with feed 0.05 mm/rev and speed 750 rpm is shown in Table 4, and it was found that the maximum temperature was reached at 24th second for the 1st experiment. Similarly, remaining experiments were carried out as per Table 3 (i.e. from experiment no. 2 to experiment no. 9), and the maximum temperature is plotted in Fig. 5 for all the three trials along with the time at which the maximum temperature was observed.

Figure 6 shows the average temperature variation during all experimental run for the machining time of 30 s. It was observed that the average maximum temperature 176.9 °C was recorded at 9th experiment at 7th second, and the average minimum temperature 152.6 °C was recorded at 1st experiment at 24th second. From Fig. 6, it was observed that during experiment nos. 4 to 9, the temperature was high during the first half from 1 to 11 s, then gradually reduces in the second half from 12 to 30s, whereas in the case of experiment nos.1 to 3, the maximum temperature reaches after 16th second and gradually reduces.

Table 2 Factors and their levels of drilling conditions for GFRP composites

Symbol	Factors	Level 1	Level 2	Level 3
F	Feed (mm/rev)	0.05	0.1	0.15
S	Spindle speed (rpm)	750	1000	1250
C	Coolant pressure (bar)	0.01	0.02	0.03

Table 3 Allocation of factors in L_9 (3^3) orthogonal array

Experiment no.	Factors		
	Feedrate (F) (mm/rev)	Spindle speed(S) (rpm)	Coolant pressure (C) (bar)
1	0.05	750	0.01
2	0.05	1000	0.02
3	0.05	1250	0.03
4	0.10	750	0.03
5	0.10	1000	0.01
6	0.10	1250	0.02
7	0.15	750	0.02
8	0.15	1000	0.03
9	0.15	1250	0.01

3.2 Drilling by external coolant method

In external coolant method, a jet of coolant is applied on the workpiece directed at the cutting zone at different pressures. All the experiments are carried out as per Table 3, and the maximum temperature is plotted in Fig. 5 for all the three trials along with the time at which the maximum temperature was observed. Figure 7 shows the average temperature variation during all experimental run for a machining time of 30 s. It was observed that the average minimum temperature and the average maximum temperature are found to be 80.8 °C at 22nd second for the experiment no. 1 and 146.1 °C at 9th second for the experiment no. 9, respectively.

From Fig. 7, it is observed that experiment nos. 7 to 9, the temperature reached the maximum within the first 9 s and then gradually decreases in the later part of the drilling operation. For the experiment nos. 4 to 6, the maximum temperature reaches in the first 15 s of the drilling operation. For the experiment nos. 1 to 3, the maximum temperature reaches within first 22 s.

3.3 Drilling by internal coolant method

In internal coolant method, the coolant is sent with different pressures through the coolant hole to the machining zone. All the experiments are carried out as per Table 3, and the maximum temperature is plotted in Fig. 5 for all the three trials along with the time at which the maximum temperature was

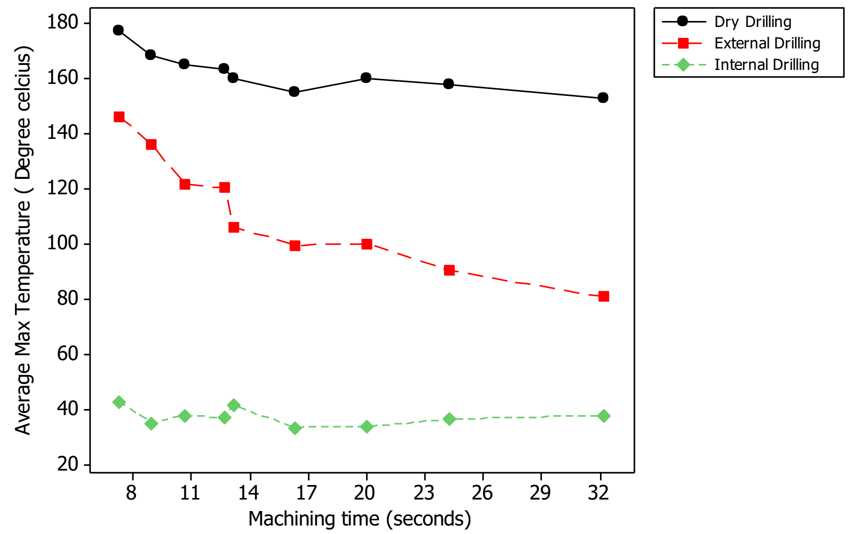


Fig. 5 Average maximum temperature against machining time for different cooling conditions

Table 4 Typical dry drilling experimental results for 0.05 mm/rev and 750 rpm

Time (s)	Trial 1 (°C)	Trial 2 (°C)	Trial 3 (°C)	Average (°C)
1	26.1	39.3	26.7	30.7
2	26.3	42.2	27.2	31.9
3	26.9	44.3	30.3	33.83
4	30.5	45.2	40	38.57
5	59.6	50	50.2	53.27
6	73	55.6	63.5	64.03
7	80.8	64.9	72.6	72.77
8	88.9	74	82.1	81.67
9	97	85.4	91	91.13
10	99	92.9	97.4	96.43
11	105.3	99.2	107.4	103.97
12	109.7	105	111.4	108.7
13	114.3	110.1	115	113.13
14	120.4	116.1	119.2	118.57
15	123.2	121	125.2	123.13
16	126.6	125.7	125	125.77
17	129.4	130.4	128.1	129.3
18	131.8	133.9	131	132.23
19	136.2	136.6	133.2	135.33
20	140.2	139	136.3	138.5
21	146.2	141.9	140.1	142.73
22	148.8	145.4	144.2	146.13
23	147	147.8	146.6	147.13
24	152.9	154.9	150	152.6
25	136	152.6	150	146.2
26	129	153.3	142.6	141.63
27	115.2	154.9	132.8	134.3
28	110.3	152.2	122.9	128.47
29	102.1	144.4	117.1	121.2
30	100.2	144.4	112.7	119.1

observed. Figure 8 shows the average temperature variation during all experimental run for a machining time of 30 s. It was observed that the average minimum temperature and the average maximum temperature are found to be 33.5 °C at 10th second for the experiment no. 4 and 42.9 °C at 5th second for the experiment no. 9, respectively.

From Fig. 8, it is observed that in experiment nos. 7 to 9, the temperature reached the maximum within the first 5 s and then gradually decreases in the later part of the drilling operation. For the experiment nos. 4 to 6, the maximum temperature reaches in the first 10 s of the drilling operation. For the experiment nos. 1 to 3, the maximum temperature reaches within first 19 s.

4 Data analysis and results

The taguchi's S/N ratio and analysis of variance are applied in this work, for the identification of the best levels of cutting parameters, significance and optimization of the parameters, and regression analysis is used for modelling of process parameters.

4.1 Experimental model for drill temperature

Statistical model based on linear multiple regression equations was developed for drilling temperature using the experimental parameters and temperature response for all the three cooling conditions as given below.

$$\mathrm{T} = c_0 + c_1 + (\mathrm{F}) + c_2(S) + c_3(\mathrm{C.P}) + \ldots\ldots + \varepsilon \qquad (1)$$

where T=drill temperature, f=feed, S=speed, C.P=coolant pressure

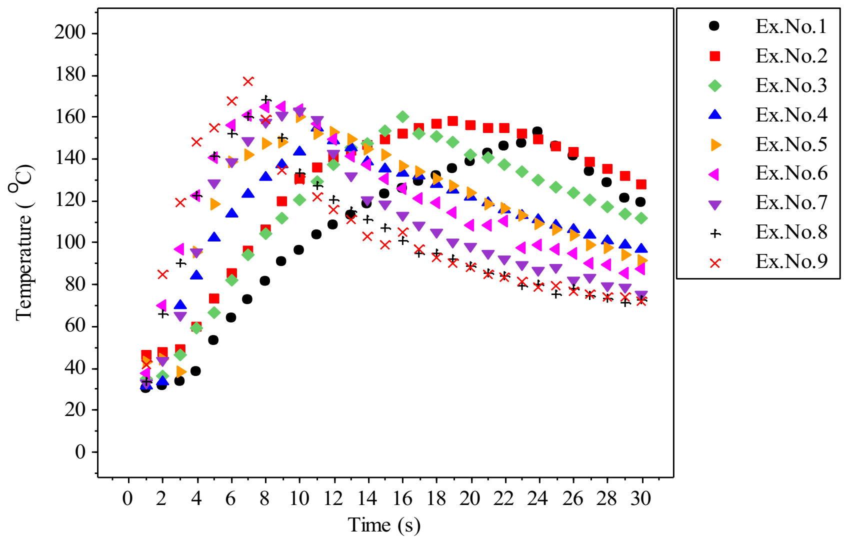


Fig. 6 Average temperature recorded during dry drilling

c_1, c_2 and c_3 are the estimates of the process parameters, and ε is error. The standard commercial statistical software MINITAB 15 is used to derive.

The linear polynomial model given below is representing the parameters as a function of temperature. But, for dry drilling, temperature is represented as a function of speed and feed.

The regression equation for drill bit temperature in dry drilling is

$$T = 129 + 127(F) + 0.0209(S) \quad (2)$$

The regression equation for drill bit temperature in external coolant is

$$T = 22.0 + 437(F) + 0.0447(S) + 4.2(C) \quad (3)$$

The regression equation for drill bit temperature in internal coolant is

$$T = 37.7 + 22.0(F) + 0.00420(S) - 33.3(C) \quad (4)$$

4.2 Validation of experimental results

To validate the experimental temperature results, temperature was measured for arbitrary cutting condition and validated with modelling temperature result.

It was found from Tables 5, 6 and 7 that percentage of error is within 2 % for dry drilling, external coolant method and internal coolant method. The instrument errors in measurement system and uncertainty of machining parameters produce uneven rate of change in temperature.

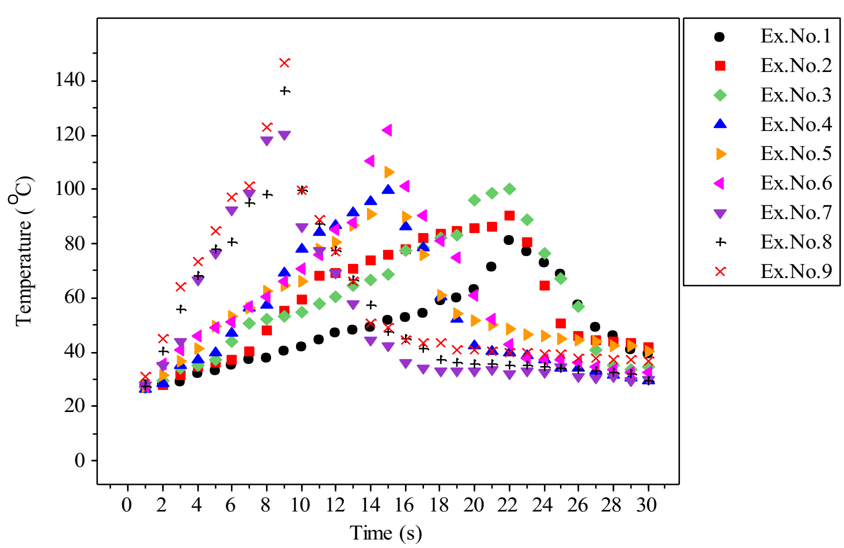


Fig. 7 Average temperature recorded during drilling by external coolant method

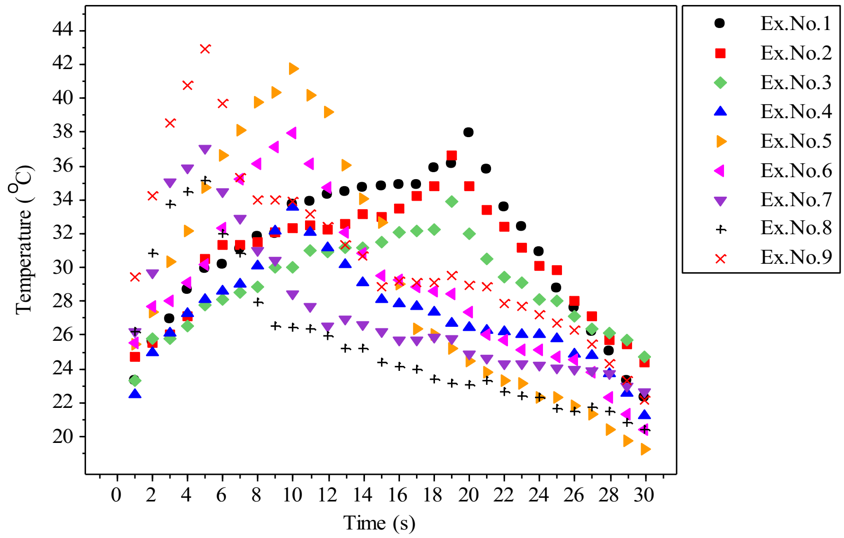


Fig. 8 Average temperature recorded during drilling by internal coolant method

This may be the reason for the error, which is experimentally reasonable.

4.3 Analysis of S/N ratio

Drill bit temperature is the output or response variable which greatly influences the quality of the product. In this study, the smaller the better characteristic is applied to determine the S/N ratio for tool temperature, since drill bit temperature is to be minimized. The S/N response graph for the drill bit temperature for dry drilling is shown in Fig. 9. From Fig. 9, we find that the optimal parameter for minimum temperature is the feed at level 1 (0.05 mm/rev) and speed at level 1 (750 rpm).

Figure 10 illustrates S/N analysis for drilling with external coolant method. It is found that low feed at level 1 (0.05 mm/rev), low speed at level 1 (750 rpm) and low coolant pressure (0.01 MPa) at level 1 are recommended since lesser temperature is observed.

From Fig. 11, we can find that low feed (0.05 mm/rev) at level 1, low speed (750 rpm) at level 1 and high coolant pressure at level 3 (0.03 MPa) are recommended for drilling with internal coolant method since less temperature is observed.

4.4 Analysis of variance

ANOVA helps in formally testing the significance of the three factors feed, speed and coolant pressure and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. The purpose of analysis of variance is to investigate the factors which significantly affect the drill bit temperature.

Table 8 illustrates the analysis of variance for dry drilling; it is observed that feed is found to be having the higher contribution 58.18 % and followed by speed 36.71 % for heat generation or raise in temperature.

From Table 9, it is observed that feed is found to be having the highest contribution of 80.70 % followed by speed of 18.91 % and coolant pressure by 0.19 %. It is observed that the influence of coolant pressure is very less in external coolant method. The reason is during drilling process, the chips which are formed during machining tend to come out of the machining zone through flute. When a jet of coolant is applied on, the workpiece directed at the cutting zone tries to reach the machining zone through the flute. Since the chips formed during machining try to come out through the flute enough, passage is not seen for the coolant to go

Table 5 Validation of result for dry drilling

S. no	Speed (rpm)	Feed (mm/rev)	Actual temperature (°C)	Predicted temperature (°C)	%Error
S. no	Speed (rpm)	Feed (mm/rev)	Actual temperature (°C)	Predicted temperature (°C)	%Error
1	750	0.05	152.6	151	1.04
2	1,000	0.15	168.3	168.9	0.35
3	1,250	0.1	165.1	167.8	1.63
4	750	0.15	163.1	163.7	0.36
5	1,000	0.1	160.1	162.6	1.56

Table 6 Validation of result for external coolant drilling

S. no	Speed (rpm)	Feed (mm/rev)	Coolant pressure (bar)	Actual temperature (°C)	Predicted temperature(°C)	%Error
1	750	0.1	0.1	101	99.6	1.38
2	1,000	0.15	0.2	136.2	133	2.34
3	1,250	0.05	0.2	99.8	100.5	0.7
4	750	0.15	0.1	122.2	121.4	0.65
5	1,000	0.05	0.3	91.2	89.81	1.52

to the machining zone. Hence, drilling with external coolant which is widely practiced may not be of good significance in machining of GFRP composites.

From Table 10, it is observed that coolant pressure is found to be having the highest contribution of 81.42 % followed by feed of 8.29 % and speed by 7.61 %. It is observed that the influence of coolant pressure is more in internal coolant method. Since the coolant is fed directly to the machining zone, the cutting edge of the drill bit is directly in contact with fresh coolant leading to less temperature of drill.

5 The effects of different cooling conditions on flank wear

Thermal conditions in drilling differ significantly from those in simple processes. In drilling, the chip is formed at the bottom of the hole and remains in contact with the drill over a comparatively long distance, which increases tool temperature. Temperatures in drilling increases with number of holes and hole depth [19].

To find out the effect of different cooling conditions on flank wear, experiment was carried out for drilling 100 holes in a glass fibre-reinforced plastic with TiN/TiAlN-coated carbide drill for feed 0.05 mm/rev, speed 750 rpm and coolant pressure 0.1 Mpa during external and internal cooling condition and 0.05 mm/rev feed and 750 rpm speed for dry drilling.

The TiN/TiAlN-coated carbide drill was subjected to aggressive abrasive action in the presence of hard glass fibres embedded inside the soft epoxy matrix. The fluctuating load acting on the cutting edge of drill bit leads to completely different wear characteristics while drilling GFRP composites. Tungsten-coated carbide, being brittle in nature, is unable to sustain high stresses and thus undergoes chipping. The cracks created were worn away with wear progress during continuous drilling. Typical variation of tool wear for different cooling conditions is presented in Fig. 12.

During dry drilling, a steep rise in temperature is attained at early stages of 0–40 holes, which is also usually associated with run in wear of the cutting edge due to chipping. At the start of drilling, the new cutting edges have sharp corner radius, carrying cutting forces over relatively small chip contact area results in high wear rate. After 40 holes, there is a rapid increase in temperature that leads to rapid flank wear attributable to thermal degradation of the tool.

In external coolant cutting conditions, the drill bit performance was better than dry drilling. This can be attributed to reduced frictional heating over tool flank and less heat exposure to substrate carbide due to the presence of coolant. The coating starts peeling from 50th hole and from there on starts peeling; there is a steady increase in flank wear.

In internal coolant drilling conditions, there is a run in wear till 20 to 25 holes. The cutting edge settles down for a steady machining phase during which there is a gradual almost linear increase in flank wear up to 93 μm. After 65 holes, there is rapid increase in flank wear.

The steady state is observed in the graph for internal coolant method from 35 to 60, whereas in case of dry drilling and external coolant method, are not found. The steady state

Table 7 Validation of result for internal coolant drilling

S. no	Speed (rpm)	Feed (mm/rev)	Coolant pressure (bar)	Actual temperature (°C)	Predicted temperature (°C)	%Error
1	750	0.1	0.1	40	39.7	0.75
2	1,000	0.15	0.2	38.2	38.54	0.89
3	1,250	0.05	0.2	38	37.39	1.6
4	750	0.15	0.1	40.1	40.82	1.79
5	1,000	0.05	0.3	33.5	33.01	1.46

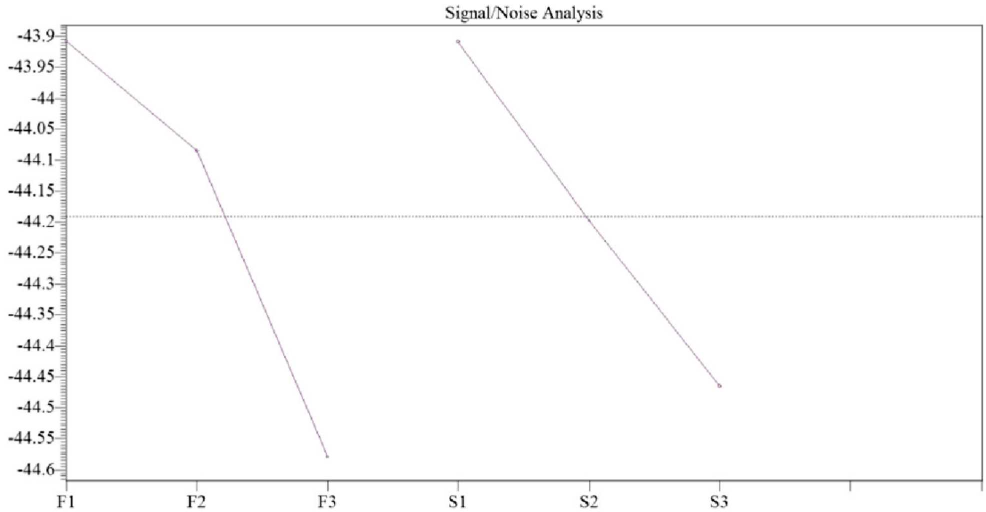


Fig. 9 S/N analysis graph for dry drilling

for internal coolant method is attained since the coolant directly injected in the flank region that reduces the rubbing action between the drill bit and GFRP where flank wear in that region is formed. The steady wear phase in flank wear is caused due to adhesion. Under the combined effect of pressure and temperature in the cutting zone, the diffusion wear phenomenon is activated. Rapid wear phase in the flank wear is due to diffusion wear.

Figure 12 shows the increase in the no. of holes in internal coolant method when compared to dry drilling and external coolant method. For the 200-μm flank wear in TiN/TiAlN-coated carbide drill, internal coolant method provides a maximum of 80 number of holes whereas in case of dry drilling, it is 45Nos, and in external coolant method, it is 60Nos. The number of holes made by the internal coolant method is 43.75 % more in comparison with dry drilling and 20 % more in comparison with external coolant method.

6 Discussion

6.1 Heat generation and its effects during drilling process

During drilling of glass fibre-reinforced polymer, the primary plastic deformation and work-tool interface at flanks, where frictional rubbing occurs, contribute more heat generation. Almost all of this energy is converted in to heat, producing high temperatures in the deformation zones and surrounding regions of the chip, tool and workpiece [20]. The temperature in the various zones affected by the cutting conditions, the cutting speed, feed, depth of cut and tool geometry. It will also depend on the properties of work material, as well as on the physical properties of the tool. The temperature increases because more heat is being concentrated or generated in a small area or less heat is being dissipated. The effect of cutting conditions will be to influence the temperature. Less obvious effects are those of tool geometry, the material and properties

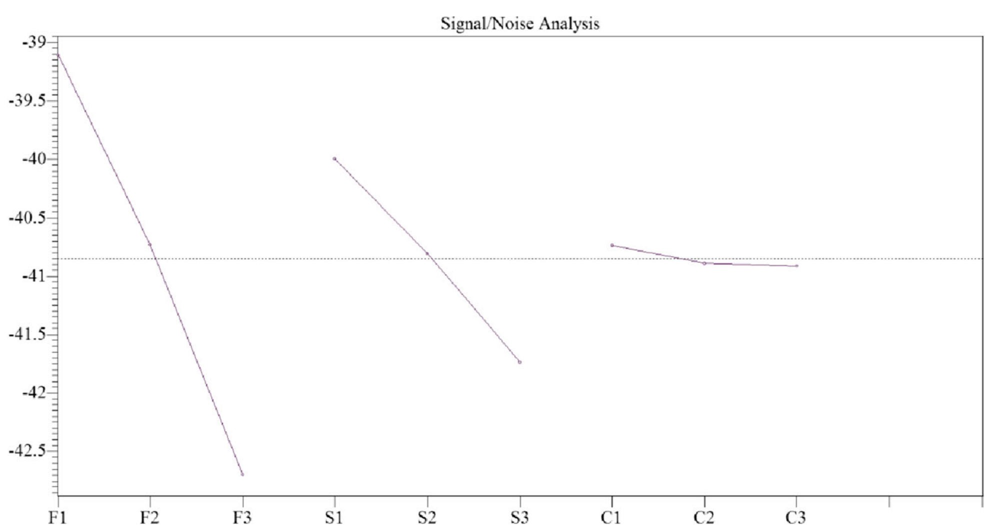


Fig. 10 S/N analysis graph for drilling by external coolant method

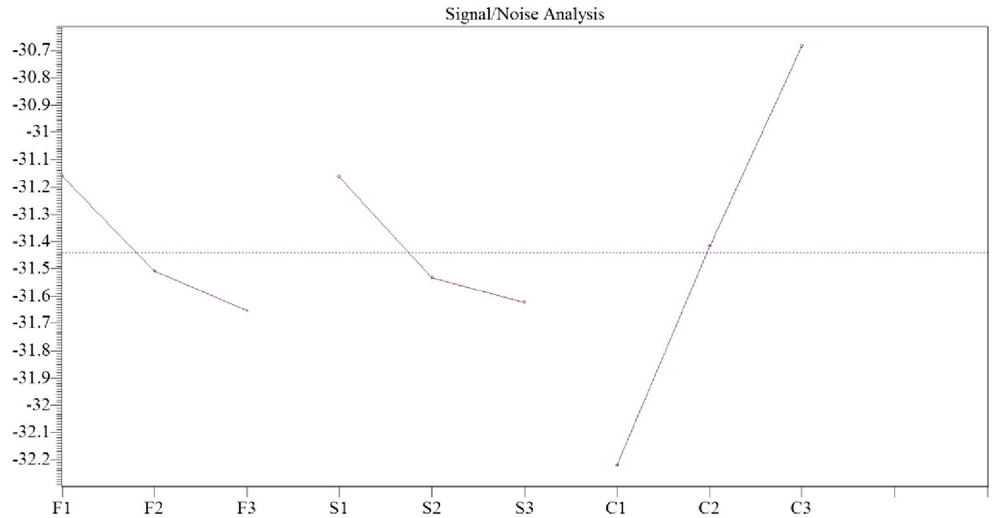


Fig. 11 S/N analysis graph for drilling by internal coolant method

of tool [21]. Increasing the cutting speed increases the rate at which heat energy is generated through plastic deformation and in the cutting zone. Similarly, increasing the feed rate also increases cutting temperature. Lack of lubrication also causes a temperature increases due to increased friction between the tool and chip. The maximum temperature occurs along the tool face, near to the cutting edge. The temperature attained in material removal process is important because they affect the form stability of tool material. Wear is the predominant cause by which the drill bit fails. Form stability of the cutting tool can be achieved by proper selection of machining parameters up to some extent.

To find out the effect of drill parameters on drill bit along with dry machining, the effect of cooling in both external and internal approaches is studied.

Flank wear and associated tool life are studied and compared for various coolant approaches.

6.2 Dry drilling

Average machining temperature for all the experiment is around 162 °C in dry drilling. The range of temperature varies from 152.6 to 176.9 °C, and fluctuation is around 25 °C. The average maximum temperature 176.9 °C was recorded at 9th experiment at 7th second, since the speed and feed given is high. In the same way, average minimum temperature 152.6 °C was recorded at 1st experiment at 24th second, since the speed and feed given are very less when compared to other experiments. During the experiment nos. 1 to 3, feed is kept constant 0.05 mm/rev and speed varied to 750, 1,000 and 1,250 rpm, as a result temperature increases gradually from 1st experiment to 3rd experiment due to significant increase in the speed. Similar inference can be referred from the graph for 4th to 6th experiment as well as 7th to 9th experiment. During the experiment nos. 4 to 9, feed is more, and hence, the machining time is less as when compared to experiment nos. 1 to 3 as shown in Fig. 6. Since the machining time is less, the cutting edges of the drill bit are subjected to severe shock leading to high temperature. This shows the significance of feed toward temperature in dry drilling. Similarly, from the ANOVA in Table 8, it is evident that the significance of feed is more followed by speed on temperature during dry drilling, since the temperature range is more for dry drilling process which promotes flank wear in the drill bit rapidly.

6.3 External coolant approach

Average machining temperature for all the experiment is around 111.2 °C in external coolant approach. The range of

Table 8 Analysis of variance for dry drilling

Source	Level (S/N)			DF	S	V	F	S’	ρ (%)
	1	2	3						
F	−43.908	−44.085	−44.579	2	0.726	0.363	46.502	0.71	58.18
S	−43.909	−44.198	−44.465	2	0.464	0.232	29.709	0.448	36.71
Error	-	-	-	4	0.031	0.008	-	-	-
(e)	-	-	-	4	0.031	0.008	-	0.062	5.11
Total	-	-	-	8	1.22	0.153	-	-	100

Table 9 Analysis of variance for drilling by external coolant method

Source	Level (S/N)			DF	S	V	F	S'	ρ (%)
	1	2	3						
F	−39.109	−40.731	−42.7	2	19.399	9.699	1,568.20	19.387	80.70
S	−39.995	−40.809	−41.736	2	4.555	2.278	368.257	4.543	18.91
Error	-	-	-	2	0.012	0.006	-	-	-
C	−40.735	−40.891	−40.915	2	0.057	0.029	4.646	0.045	0.19
(e)	-	-	-	2	0.012	0.006	-	0.049	0.21
Total	-	-	-	8	24.024	3.003	-	-	100

temperature varies from 80.8 to 146.1 °C, and fluctuation is around 65 °C. The average maximum temperature 146.1 °C was recorded at 9th experiment at 9th second, since the feed and speed given are high and coolant pressure is less. In the same way, average minimum temperature 80.8 °C was recorded at 1st experiment at 22nd second since the values of feed given followed by speed and coolant pressure were very less compared to other experiments. It can be inferred from Fig. 7 during the experiment nos. 1 to 3 that feed constant 0.05 mm/rev and speed vary to 750, 1,000 and 1,250 rpm, and coolant pressure increases to 0.1, 0.2 and 0.3 bar as a result temperature increases gradually from 1st experiment to 3rd experiment due to significant increase in the speed. This shows that the significance of coolant pressure is very less in external coolant method.

Similar inference can be referred in the graph for 4th to 6th experiment as well as 7th to 9th experiment. For experiment nos. 4 to 6, the machining time is less since feed is high, and because of this, the peak temperature has reached within 15 s. Similarly, for experiment nos. 7 to 9, the peak temperature reached within 9 s. We can infer from the Fig. 7 that the temperature increases with the increase in feed and the time taken to reach the maximum temperature increases with increase in machining time similarly from ANOVA. In Table 9, it can be observed that feed plays a major role followed by speed and coolant pressure in influencing temperature during external coolant drilling. Even though coolant was applied externally, the amount of coolant is not exactly reaching the flank region of the drill bit and completely utilized for the purpose of cooling. Hence, coolant pressure plays a very minor role in influencing temperature. But, when compared to dry drilling, external coolant method reduces temperature around 50 °C. Hence, external coolant approach reduces temperature and flank wear when compared to dry drilling.

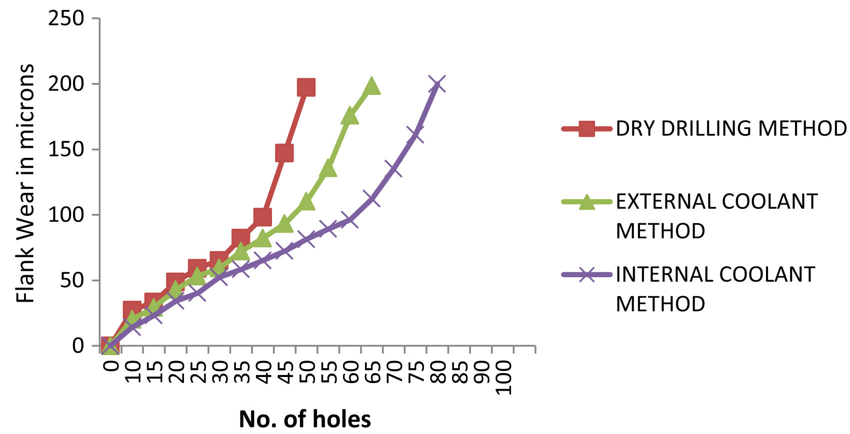
6.4 Internal coolant approach

Average machining temperature for all the experiment is around 37.38 °C in internal coolant approach. The range of temperature varies from 37.9 to 42.9 °C, and fluctuation is around 5 °C. The average maximum temperature 42.9 °C was recorded at 9th experiment at 5th second, since the speed and feed given are high and coolant pressure is less. In the same way, average minimum temperature 33.5 °C was recorded at 4th experiment at 10 s since the significance coolant pressure followed by feed and speed was very less compared to other experiments. During the experiment nos. 1 to 3, feed constant 0.05 mm/rev and speed vary to 750, 1,000 and 1,250 rpm and coolant pressure increases to 0.1, 0.2

Table 10 Analysis of variance for drilling by internal coolant method

Source	Level (S/N)			DF	S	V	F	S'	ρ (%)
	1	2	3						
F	−31.159	−31.508	−31.654	2	0.388	0.194	13.37	0.359	8.29
S	−31.163	−31.534	−31.624	2	0.358	0.179	12.354	0.329	7.61
Error	-	-	-	2	0.029	0.014	-	-	-
C	−32.221	−31.417	−30.683	2	3.551	1.775	122.451	3.522	81.42
(e)	-	-	-	2	0.029	0.014	-	0.116	2.68
Total	-	-	-	8	4.325	0.541	-	-	100

Fig. 12 The effect of different cooling conditions on flank wear



and 0.3 bar as a result temperature decreases gradually from 1st experiment to 3rd experiment due to significant increase in the coolant pressure. This shows that the significance of coolant pressure is very high and speed was very less in internal coolant method. Similar inference can be referred in the graph for 4th and 8th experiment. For experiment nos. 7–9, the machining time is less since feed is high, and because of this, the peak temperature has reached within 5 s. Since the machining time is less, the temperature generated is high for these experiments. Similarly, from ANOVA in Table 10, it can be observed that coolant pressure plays a major role followed by feed and speed in influencing temperature during internal coolant drilling. Internal coolant method reduces temperature around 124 °C when compared to dry drilling and 73 °C when compared to external coolant method.

These are the following reasons for the reduction of temperature in internal coolant approach compared with dry drilling and external coolant approach.

Internal coolant method uses the coolant injected from the bottom of drill bit and flushes away the chip formed during machining to exactly reach the cutting zone with very less time and fully utilized for the purpose of cooling; it facilitates the movement of chip and reduces the friction between the chip and workpiece and between tool and chip. Since the coolant is circulated inside the tool and also available at the outside of the tool, this accelerates the cooling effects.

In external coolant method, the coolant applied on the workpiece was passing through the clearance between the workpiece and tool where the chip coming out from the cutting zone; hence, the temperature was increased by the temperature of chip before reaching the cutting zone. But, in case of internal coolant method, the coolant temperature remains the same before reaching the cutting zone.

The pressure of the coolant was influencing more in internal coolant method than the external coolant method because the applied pressure of the coolant and the pressure of the coolant at the cutting zone are not the same in external coolant.

7 Conclusion

Heat effects in drilling are generally more severe in drilling than those in any other metal cutting operations because the drill is embedded in the workpiece; so, heat generation is localized in a small area. As the drill moves in to the workpiece, heat is continuously added to the material and continuously increase with hole depth.

The effect of various cooling conditions on temperature and flank wear on drilling of glass fibre-reinforced plastic with TiN/TiAlN-coated carbide drill was studied, and a regression model for drilling temperature with respect to machining conditions for drilling is individually developed for all the cooling conditions and validated with a minimum error of ±7 %. The following conclusions are drawn based on this study.

Internal coolant method reduces the average temperature by 76 % compared with dry drilling and 66 % compared with external coolant method. The reduction in tool temperature reduces the flank wear and increases the tool life by 43.75 % with dry drilling and 25 % with external coolant method. The maximum pressure settings in internal coolant are more effective because the high pressure of the cutting fluid displaces the fluid available in the cutting zone and fills the fresh fluid.

The investigations of drilling processes have shown that the developed test set-up makes it possible to analyse and to attain deeper knowledge about the drilling processes particularly the twist drill temperature. This scheme aids the researcher with a database of precise results about the temperature influence when using different coolant methods. The future scope of research work includes the following. The most common problem which occurs while drilling GFRP is delamination; hence, influence of cooling conditions on thrust force and delamination of GFRP have to be experimentally studied in future work.

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