Journal of the Brazilian Society of Mechanical Sciences and Engineering (2020) 42:553
https://doi.org/10.1007/s40430-020-02639-1

TECHNICAL PAPER

Design and test of a new step drill to reduce the operation time and increase the hole quality for CFRP materials

Tamer Çobanoğlu[1] · **Ulvi Şeker**[2]

Received: 11 October 2019 / Accepted: 15 September 2020 / Published online: 3 October 2020
© The Brazilian Society of Mechanical Sciences and Engineering 2020

Abstract
The usage of the composite materials, which is light and strong, has been rising thanks to the technological developments in the aerospace industries. The most important operation in the assembly process of the parts in producing the aircraft components is drilling which constitutes 50% of the total operation time. The reduction in the workmanship costs of the drilling operation is very important for the competition. In this study, a new step drill was designed to reduce the drilling operation time for drilling of Ø5.94-mm holes on carbon fiber reinforced plastic (CFRP) parts. The tests were applied by using a 12,000 rpm drill motor manually to simulate the actual process and to inspect the impact of new drill geometry on the hole quality. The result indicates that double step drill geometry with 18° nose angle reduces the drilling operation time by making the Ø5.94-mm hole in two steps instead of three steps. The cylindricity and delamination results of existing and newly designed drill geometry were compared. From results, the established new design geometry could be employed for drilling operations of CFRP materials. The time saving for one hole can be obtained as 30 s by using newly designed double step drill. The operation time can be reduced as 33% with this new drill.

Keywords Composite · Drilling time · Aerospace · Drill · Delamination · Cylindricity

1 Introduction

The aviation industry is one of the most relevant examples in which all final products must have superior quality with guaranteed minimum mechanical properties [1, 2]. The demands of the industries, like automobile, aircraft, machine tool, railways and so on, are better surface quality and longer functionality for machine parts [3, 4]. In the manufacturing of machine parts, engineers focused on how to carry out machining quickly and economically [5, 6]. The most important quality defect encountered during drilling operations on CFRP materials is the delamination occurring at the hole inlets and outlets. Even though acceptable limits are given in aviation documents, since the outcomes of the delamination are uncontrollable, it is desired not to be allowed during the processes. One of the factors that cause this defect is the cutting parameters [7]. In the thermosetting CFRP material, during the dry drilling process, the speed and material content have an effect on the maximum drilling force and maximum torque. Again, the cutting speed has an effect on the maximum torque [8]. During the process of drilling CFRP materials, the use of carbide tools is very common due to the fact that they are resistant to abrasion and are able to protect the cutting properties at high temperatures. Feed rate, cutting speed, drill diameter and drill geometry are the most important parameters that affect delamination. The increase in the feed rate has the greatest effect on the formation of delamination. In the radiographic error analysis study, again it was observed that the increase in the feed rate increased the delamination at the outlet of the hole [9]. The effect of the increase in cutting speed is not so great though [10]. In the process of drilling CFRP plate with a standard twist drill, low feed rate and high cutting speed yielded the best results [11]. It was possible to predict delamination with a mathematical model of second order, including cutting speed, feed rate and drill diameter [12]. In the process of

Technical Editor: Lincoln Cardoso Brandao.

✉ Tamer Çobanoğlu
tamercobanoglu@yahoo.com

Ulvi Şeker
useker@gazi.edu.tr

[1] Graduate School Of Natural And Applied Sciences, Gazi University, Ankara, Turkey

[2] Technology Faculty, Gazi University, Ankara, Turkey

drilling T700 CFRP material with a standard carbide drill with double margins, the best results were obtained with a cutting speed of 9000 rpm and at a feed rate of 400 mm/min [13].

In the researches on the structure of the CFRP material used, chip formation, delamination, heat formation and their effects were investigated. Chip formation was investigated in the holes drilled in unidirectional CFRP material with different fiber orientations. The delamination is reduced by decreasing the feed rate at the inlet and outlet during drilling. It has been found that a large rake angle provides good quality at the hole inlet but decreases the quality at the hole outlet [14]. It was found that the fiber orientation angle with the highest delamination was 45° [15]. In fiberglass composites with high modulus, drill warming is lower. Cutter life is prolonged in fibers designed with low strain [16].

In order to prevent delamination and to improve the quality of the hole, studies are conducted by changing the cutting geometry used for drilling the CFRP materials with different angles, number of openings and cutting materials. In the study with drills with different geometries, it is possible to prevent delamination by reducing the feed force generated during drilling by appropriate cutting speed and feed rate [17]. With the polycrystalline diamond (PCD) eight-faced drill and unidirectional CFRP composite material, the feed force during the drilling of the CFRP composite material increases with the increase in the feed rate and decreases a bit with the increase in the cutting speed. The best surface quality is achieved by the combination of high cutting speed and low feed rate [18]. In the drilling operation in CFRP unidirectional (UD) material, the primary and secondary corner lengths and angles must be taken into account in PCD drill design [19].

High-speed steel (HSS) drills are effective in the fabric CFRP material up to a depth of 27.8 mm. Carbide drills are more effective than TiAIN coating to ensure that the cutting edge remains sharp as the DLC (diamond like coating) is thin [20]. During the study of drilling operation on woven CFRP material, the effect of edge angle of the drill as one of the drill geometry properties on the drill quality for the values of 90°, 118°, 140° is observed, with the change of the geometry and the delamination occurred at the inlet and outlet of the hole seemed to change in opposite directions and it is observed that the feed rate has the greatest effect on surface damage [21].

With PCD tooling, at high-speed cutting, delamination remains at minimum. The large helix angle reduces thrust and torque in a carbide drill. The choice of cutter material directly affects the hole quality [22]. In the study with drills having four different point angles, 155°, 175°, 185°, 185°/178°, it has been seen that with the increase in the angle of the edge, the feed rate is increased, the quality at the inlet of the hole is better and the quality at the outlet of the hole is worse [23]. Experiments were carried out with different drill geometry and cutting parameters in the CFRP–aluminum sandwich structure, and it was found that the parameters with the best hole quality were at 15° helix, 130° point and 30° chisel angles [24].

The abrasions, cutting forces, temperature and surface quality of the cutting tool during the drilling process of CFRP material are related to each other. During the cutting of CFRP material, with abrasive wear on the cutter, the temperature increases at the cutting edges, which can impair the quality of the hole surface [25].

After drilling a certain number of holes in CFRP material, by transferring these results to artificial intelligence, the results can be obtained with a maximum of 0.81% error in detecting delamination at hole outlet of the obtained model [26]. A finite element analysis method was developed for the delamination detection during the CFRP drilling processes, and the relationships between feed force, clamping area of the plate and layout sequence were investigated and it was found that sufficient feed force limits the increase in delamination factor [27].

In an aircraft component assembly, most of the drill operations are done by using manual drill motors. The speed can be calculated and adjusted due to the material and diameter of the drill bit. The feed is not adjusted to a fixed value and depends on the craftsmanship of the technician. Therefore, the geometry of the drill bit has the determining importance in maximizing the performance of the drill operation, preventing delamination at the inlet and outlet of the hole and obtaining a good hole cylindricity.

However, most of the previous researches performed their experimental studies by using the drill geometry with different point angles and helix angles to determine the effect of them on the hole quality. The contribution of the recent study is designing a drill geometry to decrease the operation time and improve the hole quality. Second step, 18° and 36° nose angles parameters, which have not been studied by the previous research in the literature to the best of our knowledge, were designed, tested and compared with the single step ones to achieve this purpose. The performance of the designed drills was evaluated according to the operation time and hole quality which included the cylindricity and delamination. In addition, the individual parameters of the drill geometry with respect to the hole quality are revealed. The performance results of our experimental design verified that the new step drill decreases operation time by maintaining the hole quality.

1.1 Material and method

The aim of this empirical study is to investigate the effects of newly designed double step drill geometry on the drilling operation time and the hole quality for CFRP materials.

The difference between the previous studies and the recent study is the newly designed second step on drill geometry. The nose angles of 18° and 36° are also different compared to the previous studies dedicated to inspecting the nose angle effects on the delamination and cylindricity.

Composite materials are commonly used in aircraft manufacturing due to their lightness and high strength. In this study, the experimental tests simulate the hole drilling operation on the CFRP elevator skin of an aircraft. In the current method with existing used drilling tools an Ø5.94 mm hole is drilled on the CFRP materials in 3 steps which should be applied to eliminate delamination and obtain cylindricity intolerance as shown in Fig. 1a. The target of this study is to decrease the number of drilling steps with using the newly designed double step drill geometry by satisfying the delamination and cylindricity tolerances as well as decreasing time consuming and cost. Therefore, cutting with the newly designed drilling tool will be carried out in two steps (Fig. 1b).

The second step of drilling operation will be eliminated by using the proposed methodology. First step of drilling operation will be done by using Ø3.25-mm single step drill to make a pre-hole. Then, the hole will be finalized by using the newly designed Ø4.80 × 5.94 mm double step drill.

The scraped elevator skin manufactured by the woven method was used as the test part as shown in Fig. 2. The holes were manually drilled with a 12,000 rpm drill motor. A drill block was used to ensure that holes were perpendicular to the surface during drilling (Fig. 2). Diameter measurements of the holes were performed by a hole micrometer with 0.01 mm precision and the delamination measurements were done with Insize 200X microscope.

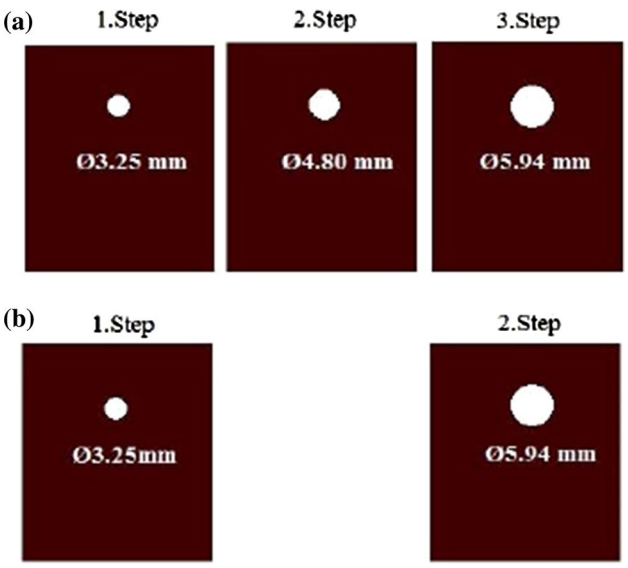


Fig. 1 **a** Existing manufacturing method, **b** improved manufacturing method

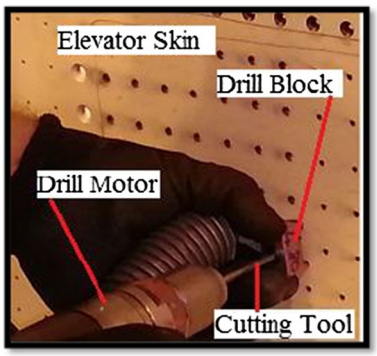


Fig. 2 CFRP test part and drilling operation

In this experimental study, very fine-grained sintered carbide cutting tools were used. The design parameters of the new drills are shown in Table 1. Test combinations are shown in Table 2.

Existing single step drill geometry with 18° nose angle is shown in Fig. 3. In Fig. 4, newly designed double step drill with nose angle 18° is shown. In Fig. 5, newly designed double step drill with nose angle 36° is shown.

All tools were manufactured with h6 tolerance. The maximum run out before grinding is 0.02 mm. Figure 6 shows the manufactured drills.

1.2 Results and discussion

This experimental investigation studied the drilling performance of newly designed double step drill geometry on CFRP material by looking at the effects of the tool geometries on the hole cylindricity and delamination. Experiments were carried out on scraped elevator skin. The main purpose of this study is to decrease the drilling time with newly designed drill geometry to satisfying the delamination and cylindricity tolerances. The conventional single step drill geometry was also tested in this study, and the results of the conventional drill geometry and newly designed double step drill geometry are compared.

1.3 Cylindricity results of conventional single step drill

The effects of the 18° nose angle single step drill geometry on the hole quality for Ø3.25 mm, Ø4.80 mm and Ø5.94 mm diameters are investigated. Figure 7 shows the result of Ø3.25-mm drill. The maximum cylindricity is obtained as 0.030 mm. It can be said that when the diameter is getting smaller, the control of the perpendicularity of the cutter along the hole axis is difficult because of the guiding of the small diameter cutter. Also, the second reason can be the fact that the first hole is opened on the virgin surface which

Table 1 Drill design parameters

Geometry type	Surface operation	Nose angle	Diameter values (mm)
Newly designed double step geometry	Coated and uncoated	18° and 36°	4.80–5.94
Existing single step geometry	Uncoated	18°	3.25; 4.80; 5.94

Table 2 Drill test combinations

No	Existing single step drill diameter (mm)	Newly designed double step drill diameter (mm)	Nose angle	Coating	Pre-hole diameter
1	Ø3.25	–	18	No	No
2	Ø4.80	–	18	No	3.25
3	Ø5.94	–	18	No	4.80
4	–	Ø4.80–5.94	18	No	3.25
5	–	Ø4.80–5.94	18	Yes	3.25
6	–	Ø4.80–5.94	36	No	3.25
7	–	Ø4.80–5.94	36	Yes	3.25

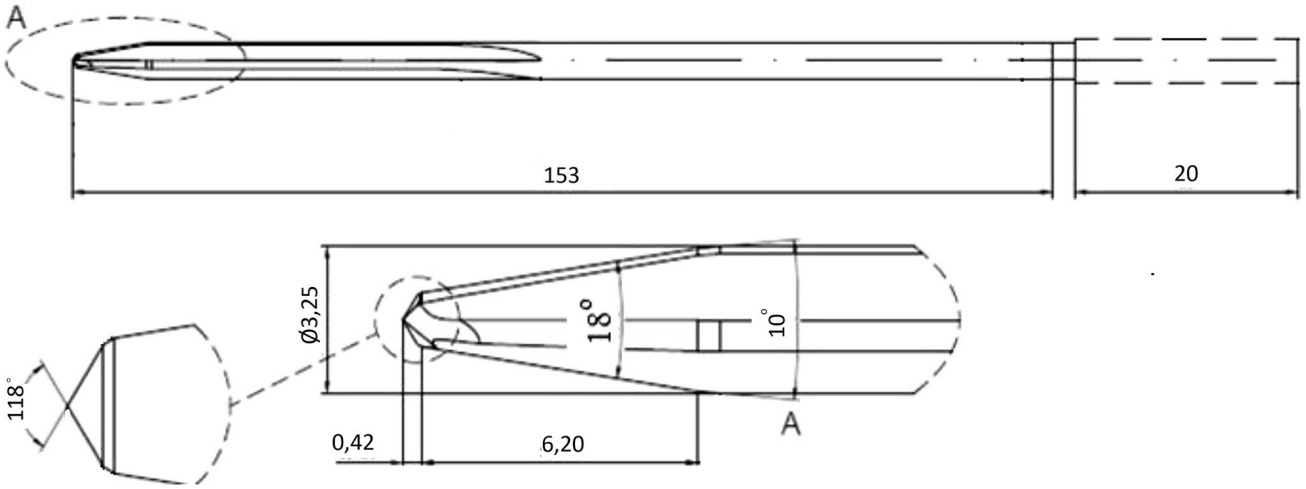


Fig. 3 Existing single step drill with 18° nose angle geometry

requires more feed force and control of the cutter to keep it perpendicular to the part surface.

Figure 8 shows the cylindricity result of Ø4.80-mm drill. Before drilling with 4.80-mm-diameter drill, 3.25-mm-diameter drill is used to make a pre-hole. Then, Ø4.80-mm hole is drilled over the Ø3.25-mm pre-hole. Therefore, the thrust force at the entrance of the hole is smaller than the one without pre-hole which guides the cutter until finishing. That can be helpful to obtain the cylindricity in tolerance.

Figure 9 shows the cylindricity results of Ø5.94-mm drill. All the results are in tolerance for Ø5.94-mm hole because it is drilled over Ø4.80-mm pre-hole. Drilling of bigger size hole directly on CFRP parts causes difficulty to obtain the cylindricity in tolerance because of the high feed force requirements that is very difficult to obtain by manually drilling which hardens the guiding of the cutter along the hole axis. Because of that reason multistep drilling operation is preferred instead of single step drilling operation.

1.4 Cylindricity results of double step drill

Figure 10 shows the cylindricity results of Ø4.80-mm single step and Ø4.80–5.94-mm double step drills. For this study, firstly Ø3.25-mm pre-hole is drilled on the CFRP part, then five holes are drilled with Ø4.80-mm drill and five holes are drilled with Ø4.80–5.94-mm double step drill. One of the results of the Ø4.80-mm single step drill is out of tolerance which is 0.007 mm. On the other hand, the results of the Ø4.80–5.94-mm double step drill are all in tolerance. Figure 11 shows the comparison of cylindricity results of Ø5.94-mm single step and Ø4.80–5.94-mm double step drills. Two of the results of the single step drill are out of

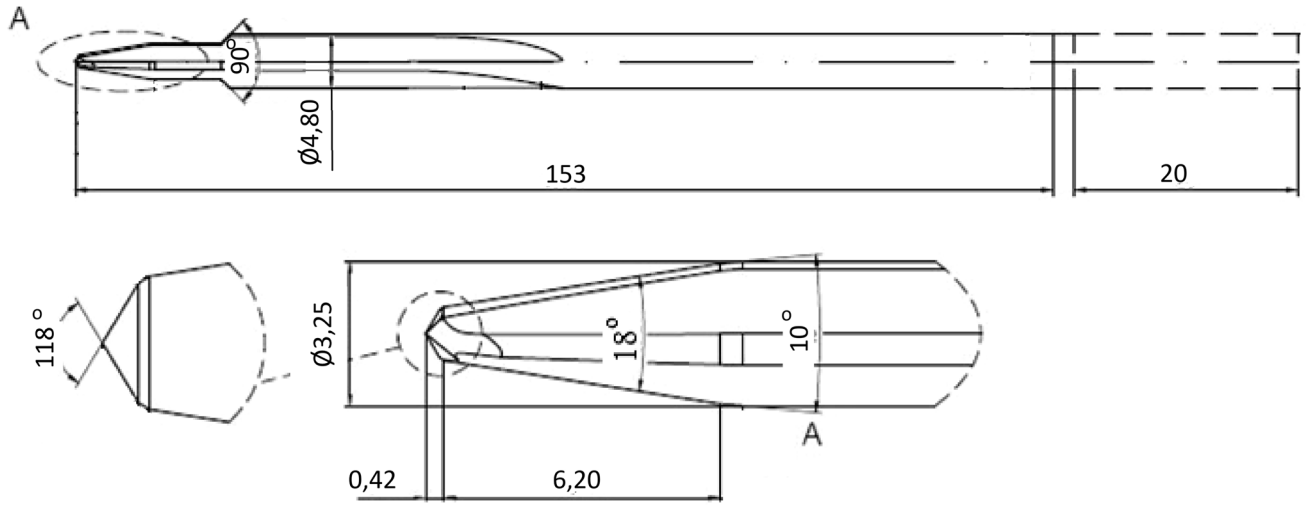


Fig. 4 Newly designed double step drill with 18° nose angle geometry

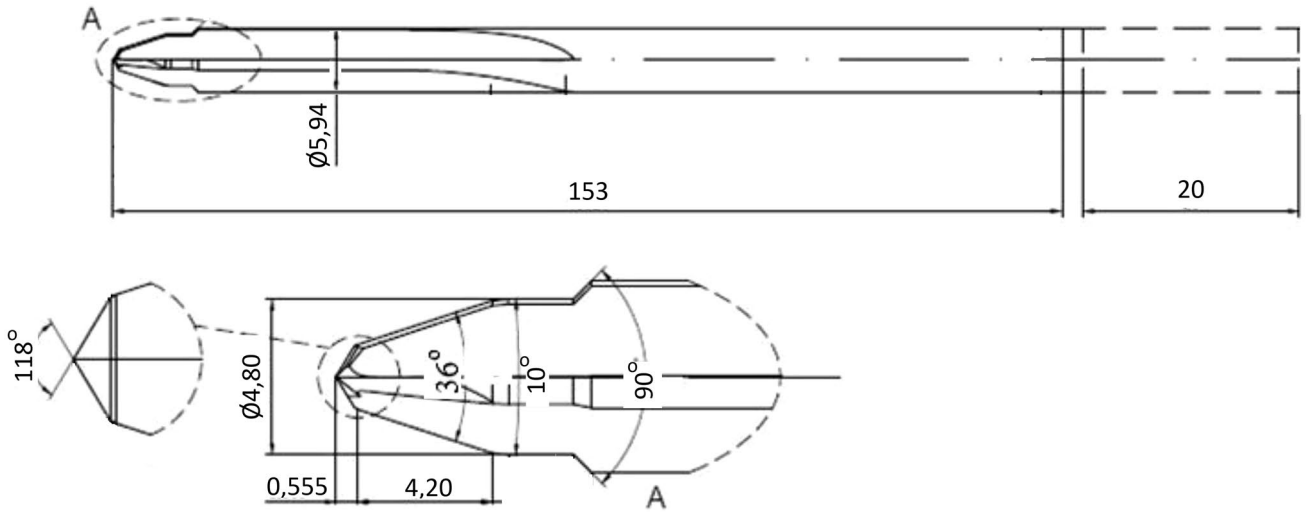


Fig. 5 Newly designed double step drill with 36° nose angle geometry

tolerance contrarily of the double step drill. It can be said that the first step of the double step drill acts as a pilot and helps to keep the cutter on the hole axis.

1.5 The effect of nose angle on cylindricity

The effect of the nose angle on cylindricity is studied and the results are shown in Fig. 12. When the nose angle is increased from 18° to 36° the cylindricity is getting out of tolerance. The higher nose angle requires higher feed force which is very difficult to obtain by the hand drilling operation. Therefore, the control of the cutter is not easy to keep the cutter axis on the hole axis.

The effect of the nose angle of the coated drill on cylindricity is also studied. Figure 13 shows that cylindricity results of 18° nose angle are better than 36° nose angle for Ø4.80–5.94-mm double step drill as obtained with the uncoated drill. Although the coating is important to reduce the wearing of the cutting edges especially working on the CFRP materials, which is very abrasive, coated drill does not result in better cylindricity than the uncoated drill. The coating is a high-cost application and prevents to make re-sharpening of the cutter.

1.6 The effect of coating on cylindricity

The effect of coating on cylindricity was determined for double step 18° nose angle drill geometry. Figure 14 shows that the cylindricity results of the uncoated drill are better than the coated one. Although coating improves the cutter life by

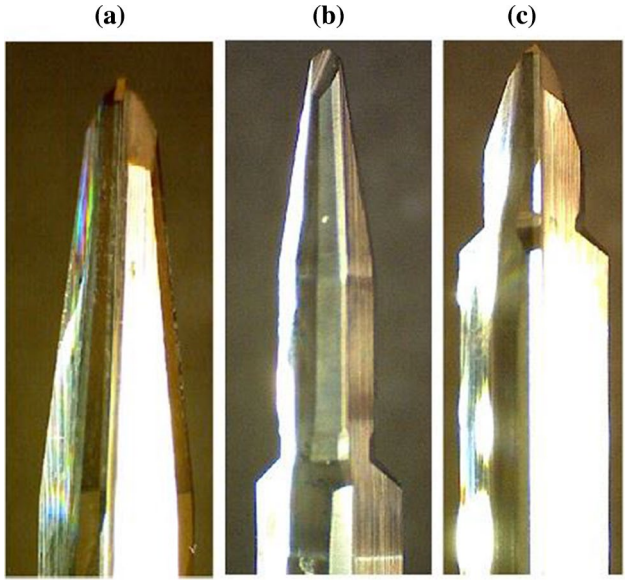


Fig. 6 **a** 18° existing drill geometry, **b** 18° double step drill geometry, **c** 36° double step drill geometry

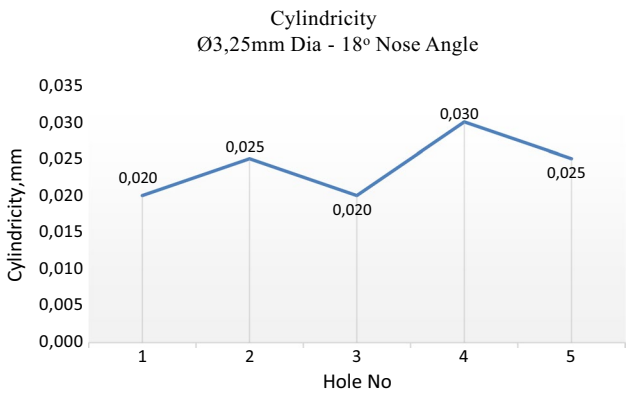


Fig. 7 Cylindricity results of Ø3.25-mm drill

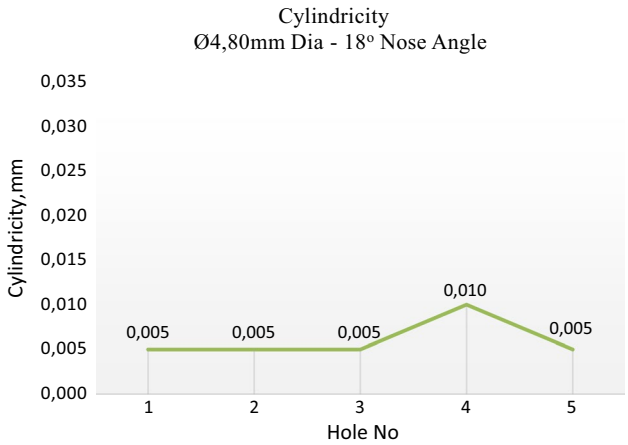


Fig. 8 Cylindricity results of Ø4.80-mm drill

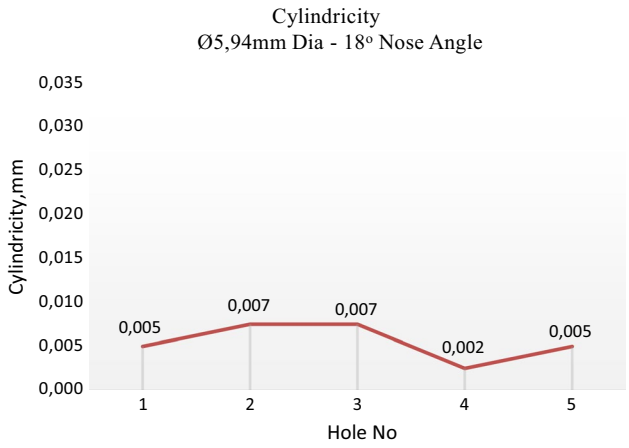


Fig. 9 Cylindricity results of Ø5.94-mm drill

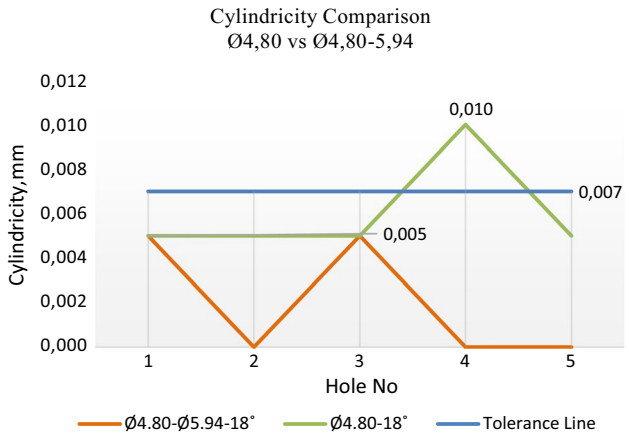


Fig. 10 Cylindricity results comparison of Ø4.80-mm and Ø4.80–5.94-mm drills

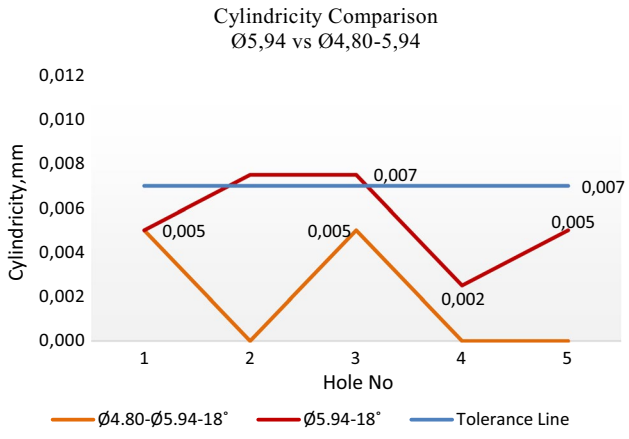


Fig. 11 Cylindricity results comparison of Ø5.94-mm and Ø4.80–5.94-mm drills

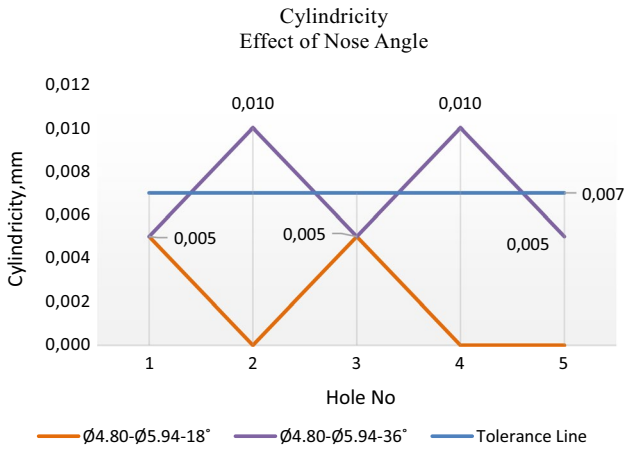


Fig. 12 Effect of nose angle on cylindricity

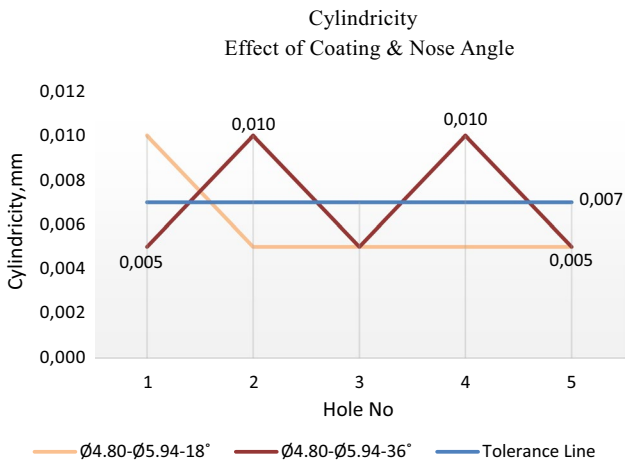


Fig. 13 Effect of nose angle on cylindricity for coated double step drill

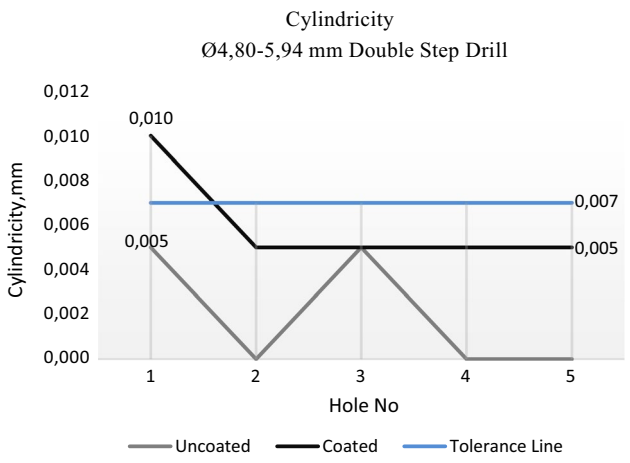


Fig. 14 Effect of coating on cylindricity of double step drill

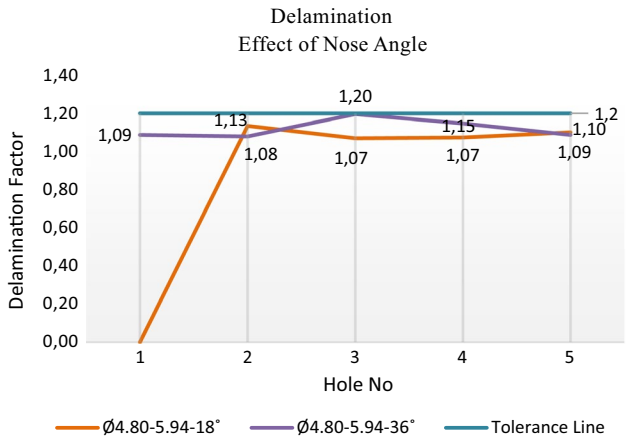


Fig. 15 Effect of nose angle on delamination

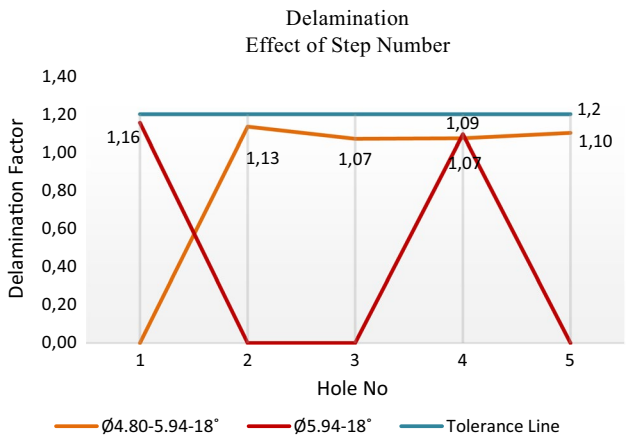


Fig. 16 Effect of step number on delamination

depending on the type of the coating, it creates more cutting and thrust forces which make it difficult to drill a hole manually. When the thrust and cutting forces are increased, the aligning of the cutter at inline position is getting difficult. Therefore, even if the movement is small, it affects the cylindricity of the hole.

1.7 Delamination results

Especially at the exit of the hole, delamination and uncut fibers are occurred according to the drill geometry and high feed force. Figure 15 shows the effect of nose angle on delamination for Ø4.80–5.94-mm double step drill. When the step angle is increased from 18° to 36° the delamination factor is increasing.

The effect of step number was studied and the results are shown in Fig. 16 which shows the comparison of Ø4.80–5.94-mm double step drill and Ø5.94-mm single step drill results. The results of these two drills are under

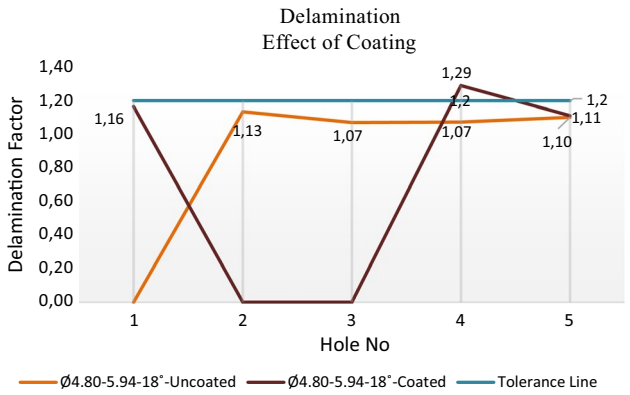


Fig. 17 Effect of coating on delamination

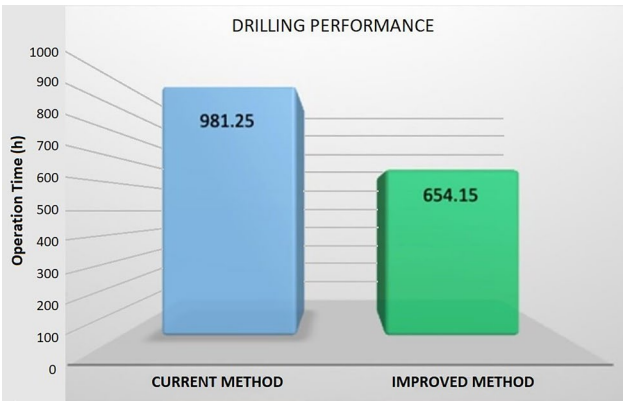


Fig. 18 Drilling performance results

tolerance line. In fact, the double step drill combines Ø4.80-mm and Ø5.94-mm drilling operations, which must be applied one after another while using single step drills, to allow one shot drilling. Because the aim of this study is to improve the drilling operation by decreasing the time and keep the quality of the hole in tolerance, the results of the double step drill are very suitable to use for this aim. By choosing the lower nose angle, delamination can be kept in tolerance.

Figure 17 shows the effect of coating on delamination for Ø4.80–5.94-mm step drill. It is seen that one of the results is out of tolerance. The coating applied to the cutting edge protects this edge from wearing, but the coating affects the cutting performance of the drill in a negative way. The thrust force occurred by using a coated carbide drill is higher than that of the thrust force occurred by using an uncoated carbide drill. This condition is related to the growing cutting-edge thickness and decrease in sharpness of the cutting edge [28].

1.8 Drilling time performance results

The processing time for drilling each hole was calculated using both existing drilling tool and newly designed drilling tool. These calculated processing times are compared each other. In order to produce the desired geometry, 250 pieces of drilling must be applied on the workpiece. Therefore, the total gain time is calculated by multiplying by 250. Then, we compare these drilling tools to determine the time spent.

By using the newly designed double step drill, the drilling operation time decreased from 1.5 to 1 min per hole. On the component, there are 250 holes to drill at Ø5.94 mm. By this study, the total time gain is 125 min (2.1 h) per component. The performance results are shown in Fig. 18.

One hundred and fifty-seven components are manufactured annually in the company where the experiments are carried on and the total time gain is 327.1 h (20.4 days) per year. The total operation time is 981.25 h per year with the current method and 654.15 h per year with the newly improved method. The results show that the production time for the same number of items can be shortened 327.1 h by using this newly designed double step drill. This means the new design can provide great savings in terms of labor costs and energy consumption, diminishing rework or reject rates and scrap. Higher quality of the parts produced also contributes to the whole process of aircraft production and increases revenues. Further studies can focus on the aggregate gains of using this new design in terms of labor costs and energy savings in the aviation industry. As the emissions of greenhouse gases are increasing concern due to climate change issue, the importance of the gained energy by adopting single applications like our study proposes could not be an underestimated contribution.

2 Conclusion

In this study, newly designed drill geometries were tested on CFRP material to see the effect of nose angle, step number and coating on hole cylindricity and delamination. Drilling process was carried out with hand-operated pneumatic drill motor with 12,000 rpm speed under dry drilling condition. The best delamination results were obtained with 18° nose angle and uncoated drill. The best cylindricity results were obtained with 18° nose angle double step drill.

To see the effect of nose angle 18°, 36° nose angle drills were used. For single step and double step geometries, the best cylindricity and delamination results were obtained with 18° nose angle. It is proved that the lower nose angle gives the best quality results for CFRP materials.

Single step and double step drills were designed and tested to see the effect of the step number on cylindricity and delamination. No matter the drill was coated or uncoated, the best cylindricity and delamination results were obtained with

double step drill. The first step acts as a pilot and guides to the second step of the drill. Therefore, the final hole size can be drilled at one step which eliminates the mismatch hole center problem which can be occurred by two drilling steps.

The best cylindricity results were obtained with uncoated drills in line with the previous literature. This study also provided evidence that the cutting edge condition is better with an uncoated cutting edge than the coated one as the coating material put an extra layer on the edge and unsharpened the edge.

The newly designed double step drill can be used for the drilling operations instead of two single step drill. The drilling operation steps decreased from three to two by using newly designed drill. This provides 0.5 min of time saving per hole. It means 327.1 h are saved annually in this application which increases productivity by employing fewer workhours as well as improving quality.

Funding This research was supported by Scientific and Technological Research Council of Turkey (1140164). The cutting tools were manufactured by Karcan Cutting Tool Company.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

References

1. Kahraman MF, Bilge H, Öztürk S (2019) Uncertainty analysis of milling parameters using Monte Carlo simulation, the Taguchi optimization method and data-driven modeling. Mater Test 61(5):477–483
2. Cobanoglu T, Ozturk S (2015) Effect of burnishing parameters on the surface quality and hardness. Proc Inst Mech Eng Part B J Eng Manuf 229(2):286–294
3. Ozturk S, Altan E (2012) A slip-line approach to the machining with rounded-edge tool. Int J Adv Manuf Technol 63(5–8):513–522
4. Kahraman MF, Öztürk S (2019) Experimental study of newly structural design grinding wheel considering response surface optimization and Monte Carlo simulation. Measurement 147:106825
5. Öztürk S, Kahraman MF (2019) Modeling and optimization of machining parameters during grinding of flat glass using response surface methodology and probabilistic uncertainty analysis based on Monte Carlo simulation. Measurement 145:274–291
6. Ozturk S, Altan E (2012) Design a computer aided quick-stop device for study of dead metal zone formation. J Braz Soc Mech Sci Eng 34(4):501–505
7. Ozturk S, Altan E (2012) Slip-line metal cutting model with negative rake angle. J Braz Soc Mech Sci Eng 34(3):246–252
8. Perez JLM, Royer R, Merson E, Lockwood A, Soberanis SA, Marshall MB (2016) Influence of workpiece constituents and cutting speed on the cutting forces developed in the conventional drilling of CFRP composites. Compos Struct 140:621–629
9. Durao LMP, Tavares JMRS, Albuquerque VHC, Marques JFS, Andrade ONG (2014) Drilling damage in composite material. Materials 7:3802–3819
10. Nagaraja R, Rangaswamy T (2018) Drilling of CFRP and GFRP composite laminates using one shot solid carbide step drill K44. AIP Conf Proc 1943(1):020025
11. Melentiev R, Priarone PC, Robiglio M, Settineri L (2016) Effects of tool geometry and process parameters on delamination in CFRP drilling:An overview. In: 3rd CIRP conference on surface integrity, vol 45, pp 31–34
12. Krishnamoorthy A, Boopathy SR, Palanikumar K (2009) Delamination analysis in drilling of CFRP composites using response surface methodology. J Compos Mater 43:2885–2902
13. Ali M, Xiang L, Yue D, Liu G (2018) Assessment of cutting performance of cemented tungsten carbide drills in drilling multidirectional T700 CFRP plate. J Manuf Mater Process 2(3):43
14. Sauer K, Dix M, Putz M (2018) Process forces analysis and a new feed control strategy for drilling of unidirectional carbon fiber reinforced plastics (UD-CFRP). J Manuf Mater Process 2:46
15. Bonnet C, Poulachon G, Rech J, Girard Y, Costes JP (2015) CFRP drilling: fundamental study of local feed force and consequences on hole exit damage. Int J Mach Tools Manuf 94:57–64
16. Royer R, Merson E (2013) Influence of CFRP properties on drilling. In: 21st Congres Francais de Mecanique, pp 26–30
17. Marques AT, Durao LM, Magalhaes AG, Tavares JM (2009) Delamination analysis of carbon fibre reinforced laminates: evaluation of a special step drill. Compos Sci Technol 69(14):2376–2382
18. Eneyew ED, Ramulu M (2014) Experimental study of surface quality and damage when drilling unidirectional CFRP composites. J Mater Res Technol 3(4):354–362
19. Karpat Y, Bahtiyar O, Deger B, Kaftanoglu B (2014) A mechanistic approach to investigate drilling of UDCFRP laminates with PCD drills. CIRP Ann Manuf Technol 63:81–84
20. Sakamoto S, Kajiwara Y, Yasui H (2007) Precision drilling of CFRP (carbon fiber reinforced plastics) with coated tools. In: 22nd annual meeting of the american society for precision engineering, ASPE 2007
21. Feito N, Alvarez JD, Alvarez AD, Cantero JL (2014) Experimental analysis of the influence of drill point angle and wear on the drilling of woven CFRPs. Materials 7:4258–4271
22. Madhavan S, Prabu SB (2012) An experimental study of influence of drill geometry on drilling of carbon fibre reinforced plastic composites. Int J Eng Res Dev 3(1):36–44
23. Heisel U, Pfeifroth T (2012) Influence of point angle on drill hole quality and machining forces when drilling CFRP. In: 5th CIRP conference on high performance cutting, pp 471–476
24. Hassan MH, Mahmud AS, Abdullah J (2018) Effects of twist drill geometry and drilling parameters on CFRP/aluminum stack up in single shot drilling. SF J Mater Res Lett 2(2):1–14
25. Ramirez C, Poulachon G, Rossi F, Saoubi RM (2014) Tool wear monitoring and hole surface quality during CFRP drilling. In: 2nd CIRP 2nd CIRP conference on surface integrity, vol 13, pp 163–168
26. Krishnamoorthy A, Boopathy SR, Palanikumar K (2011) Delamination prediction in drilling of CFRP composites using artificial neural network. J Eng Sci Technol 6(2):191–203
27. Feito N, Lopez-Puente J, Santiuste C, Miguelez H (2014) Numerical prediction of delamination in CFRP drilling. Compos Struct 108:677–683
28. Bayraktar S (2018) Assessment of cutting performance on drilling with different drilling methods of fiber reinforced polymer composites: a literature review. J Fac Eng Archit Gazi Univ 33(2):629–647

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.