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International Journal of Machine Tools & Manufacture 46 (2006) 70–75

INTERNATIONAL JOURNAL OF
MACHINE TOOLS & MANUFACTURE
DESIGN, RESEARCH AND APPLICATION

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Drilling of carbon composites using a one shot drill bit. Part I: Five stage representation of drilling and factors affecting maximum force and torque

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Received 23 September 2004; accepted 22 March 2005
Available online 6 June 2005

Abstract

The thrust force and torque produced during drilling contain important information related to the quality of the hole and the wear of the drill bit [1]. In this paper, the force and torque produced during drilling of carbon fibre using a 'one shot' drill bit is investigated. The signals in the time domain were divided into stages and common problems and defects associated with each stage discussed. It is also shown how tool wear and thickness of the workpiece affect the thrust force and torque throughout the drilling process. The findings of this paper are used to develop a mathematical model of the maximum thrust force and torque as described on Part II of this paper and are a valuable reference for future optimisation of drilling carbon composites with a 'oneshot' drill bit.

Keywords: Drilling; Carbon composite; Tool wear

1. Introduction

Although carbon fibre is not metal, for many years industry has applied the theory: 'cut it like metal'. The results of this theory were often poor finish quality and excessive tool wear. For the applications where the quality demand was higher, special drill bits have been designed for drilling composites, to improve performance compared with twist drills [2–5]. There are several common problems associated with drilling carbon fibre, with delamination and excessive tool wear usually reported as the biggest concern [6]. Melting and softening of the matrix, fibre pull-outs and scorching of the surface can also be concerns. Delamination usually occurs when the last plies of the material do not withstand the force exerted by the drill bit's chisel edge. Several authors have studied this phenomena [7–9] and some avoid delamination by means of controlling the thrust force at breakthrough [2,5,10].

The chip produced during drilling of carbon composites is a very abrasive dry dust. The ineffective extraction of the chip is one of the major reasons for high tool wear rates. Tool wear is also related to delamination, as the force necessary to cut the material increases with tool wear [11–13]. Many authors have studied the tool wear process for drilling carbon composites as well as the effect of tool wear on the drilling forces and quality of the holes produced [14–19]. Mostly, these studies are done using twist drills.

A better understanding of the drilling of carbon composites with other shaped drill bits is still necessary for further improvement and optimization of the drilling process. In this paper, the drilling process of carbon composite using an 'one shot' drill bit will be analysed. The thrust force and torque produced during drilling are investigated, divided into stages and each stage related to common defects. The effect of tool wear on the forces will also be studied. This provides the foundation for more accurate modelling of this process, as outlined in part 2 of this work, leading to the improvement of quality and productivity of the drilling process.

2. Experimental setup

The experiments were undertaken using a test bed dedicated to drilling (see Fig. 1). The spindle is driven by an AC motor and the work piece is fed to the drill by means of

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doi:10.1016/j.ijmachtools.2005.03.015

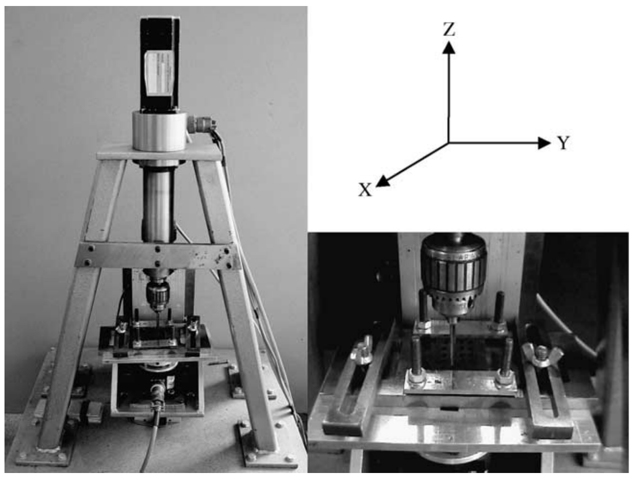

Fig. 1. Drilling test bed.

a DC motor coupled to a linear screw. A 6-axis force sensor supports the clamping system for the sample and measures the thrust force and torque during drilling. A National Instruments data acquisition board is used to control the spindle speed and feed rate of the drilling process while reading and saving data from the force sensor at 1 KHz. The data obtained from drilling is filtered in software with a low pass filter set to 10 Hz.

A 4.9 mm drill bit (Fig. 2) similar to those supplied by Sterling Carbide, Inc. (http://www.sterlingcarbide.com/series_3200.htm) was used for the experiments. This drill bit has been designed for drilling carbon composites and consists of four straight flutes with two cutting angles. Its design is similar to the commonly used 'dragger' drill bit. The straight flutes are recommended for the quick evacuation of the chip. Another important characteristic of this drill bit is the web, which comes to a point decreasing the thrust force required to drill. The two different cutting angles drill and ream the hole, thus finishing it in one operation (hence 'one shot').

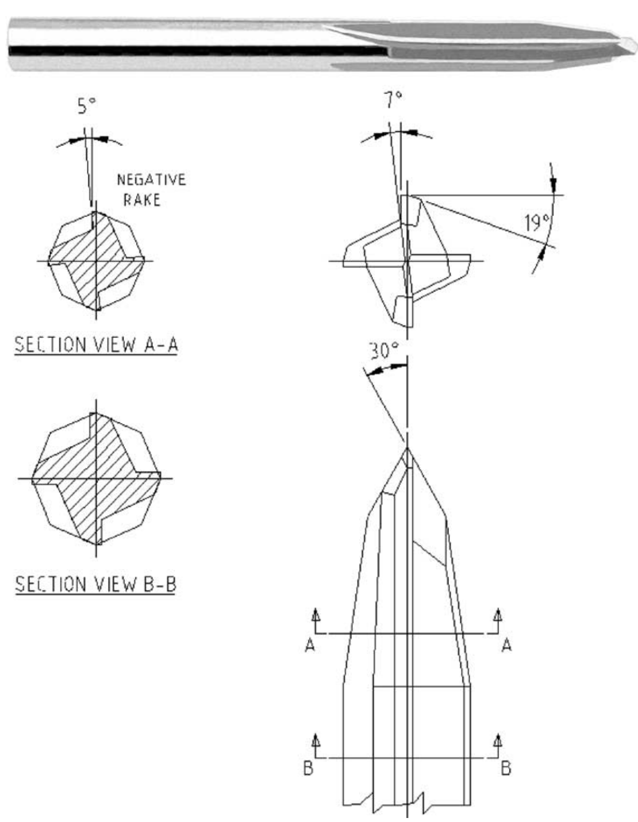

Fig. 2. One-shot drill bit.

A 2 mm and a 5.2 mm thick carbon-epoxy composite were used in the experiments discussed here. The carbon fibre plates were cut to 7×5 cm specimens in order to fit the test rig and three different layouts used: single plates of depths 2 and 5.2 mm, and a stack of two 2 mm (making a total 4 mm to be drilled) since it is common in industry to drill through two plates in order to fasten them together afterwards. Over 350 holes were drilled for this study. Each hole was drilled at constant spindle speed and feed rate. The spindles used were 750, 1000 and 1500 rpm while the feed rates were 0.75, 1 and 1.5 mm/s. Hence, there are eight different feeds varying from 0.03 to 0.12 mm/rev. The range of settings used was conservative in order to avoid chatter problems that might arise for higher spindle speeds.

3. Thrust force, torque and drilling stages

The typical thrust forces F_Z and spindle torques T_Z produced during drilling of carbon fibre using the 'one shot' drill bit can be seen in Fig. 3. The shape of these forces relates to the shape of the drill bit and the thickness of the workpiece. Different drilling settings do not alter the general shape but do alter the magnitude of thrust force and torque. The thickness of the workpiece also affects the value of

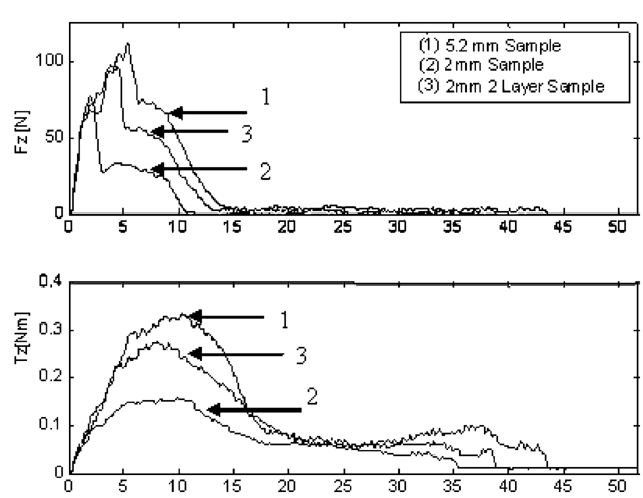

Fig. 3. Typical thrust force and torque at 0.06 mm/rev.

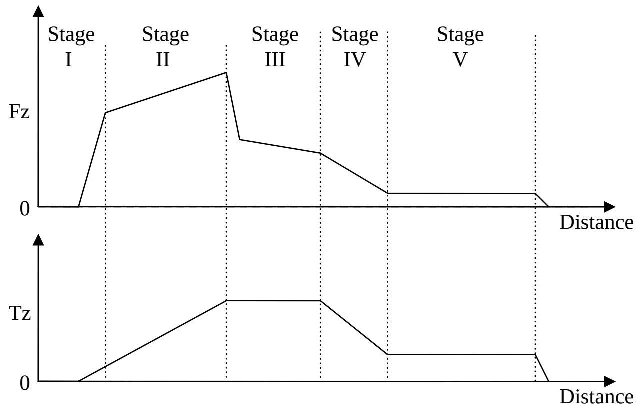

Fig. 4. Drilling stages.

the thrust force. The drilling process can be better explained if divided into five drilling stages (as shown in Fig. 4):

3.1. Stage I entrance

The drill bit approaches the workpiece in Stage I, the chisel edge makes contact with the workpiece and 'punches' its way into the sample. During this stage thrust force increases very rapidly mostly because of the 'extrusion' action of the chisel edge. The torque also increases but at a much slower rate than the thrust force. The slow increase of the torque relates to the small diameter of the drill bit at the tip. Possible problems that might arise during stage I are skidding, wandering or deflecting of the drill bit all of which affect the positioning of the hole.

3.2. Stage II drilling

The material removal starts at Stage II as the cutting lips engage the workpiece. During this stage, the thrust force increases steadily but at a slower rate as the cutting lips work their way in. The torque increases steadily throughout this stage. In Fig. 3, a sudden drop of thrust force could be seen after about 2 s on the 2 mm double layer sample. This is related to the passage from one layer of material to the other. Although the layers are held firmly together, the bottom surface of the top layer is fairly rough creating an air gap between layers. Due to the air gap the thrust force created by the extrusion action of the chisel edge will momentarily disappear but its value will pick up quickly as the drill bit encounters the second layer. It is expected that the thrust force will drop more or less depending on the size of the air gap. The passage from one layer to the other does not affect the torque and does not affect any of the quality measures substantially. Hence, for simplicity this drop in thrust force will be ignored.

Delamination and tool wear are commonly associated with stage II due to the high values of thrust force and torque. The risk of delamination is especially high at the end of this stage as the last plies of material are pushed by the chisel edge.

3.3. Stage III drilling and reaming

Stage III starts when the chisel edge reaches the bottom surface of the workpiece. The thrust force suddenly drops when the chisel edge comes out of the workpiece. As the drill bit makes its way through the hole, the cutting lips come out of the hole and the reaming flutes enter the workpiece. Hence, the drilling is replaced by the reaming action. The thrust force decreases until the cutting lips are out of the hole. The torque increases very slightly during this stage. The maximum torque is attributed to high frictional forces between the lands of the drill and the wall of the hole [1]. It might be expected that the torque should reach its peak value when the cutting lips are fully engaged, because this is when the area of the drill in contact with the surface of the hole is at a maximum. With high temperatures, the friction would also increase because of the thermal expansion of the composite which would squeeze the drill. However, in the present situation, the chisel edge extrudes from the workpiece before complete penetration making the prediction of when the maximum torque should occur harder to accomplish. During the experiments it was observed that the peak torque occurred at any time during stage III, including at the very beginning. To simplify the model, the torque in this stage is represented by a straight line. This is a fair approximation taking into consideration that in most cases the torque varies only very slightly.

This stage combines both drilling and reaming and therefore problems associated with both cutting processes can occur. Delamination is possible as the last plies are drilled to the final size although the risk is smaller than the previous stage since the thrust force is lower. Surface finish problems can arise in this stage as the transition in the cutting surfaces might cause some vibration or even chatter.

3.4. Stage IV reaming

Stage IV represents the reaming process. The drilling has finished and the drill bit is reaming the hole to its final size. Problems occurring in this section are related to the final size and finish of the hole (reaming is more prone to vibrations and chattering than drilling because of the reduced stiffness of the drill bit/workpiece system).

3.5. Stage V backing out

The drill bit backs out of the workpiece in Stage V. Reaming will continue while there is contact between the workpiece and the drill bit, altering the size and finish of the hole. During this stage both thrust force and torque maintain the same values as for the previous stage. In practice, the only difference between stage IV and stage V is the direction of movement. The cutting action and possible quality problems arising are the same for both stages.

4. Effect of tool wear

Tool wear is directly related to drilling time and consequently to the number of holes drilled with a given drill bit [16,20]. The thrust force and torque produced by a drill bit at different stages of the drill bit life can be compared. In order to allow comparison, holes drilled with the same settings and sample thickness were used. Fig. 5 shows typical examples of thrust force and torque produced at different stages of the drill bit life (represented by the hole number) for each sample thickness tested.

From the experiments it can be seen that thrust force increases with number of holes drilled. Although thrust force has increased throughout the course of the drilling process, the increase is more noticeable just before breaking through, which suggests that the primary cutting surfaces of the drill bit might be wearing out more than the rest of the body of the drill bit. This agrees with the work published by Lin [16] which reports that when drilling composites at the high speed of 38 650 rpm the drill wears first in the outer cutting edges. Comparing the different thicknesses it can be seen that the effect of tool wear is more prominent when drilling thinner samples. A possible explanation for this might be that for thicker samples the total thrust force produced is a sum of the thrust force from affected and non affected areas of the drill bit, and therefore the overall thrust force increase is not as pronounced as for thinner samples. The torque produced did not show significant changes over the range of number of holes analysed. This was true for all the samples tested.

The previous analysis looked at the thrust force increase against time. Another way of analysing the data is to plot the maximum thrust force and torque against the feed rate to find the effect of tool wear for different feeds. Fig. 6 shows the maximum thrust force and torque produced while drilling a 2 mm sample at the eight different feeds considered and at different stages of the drill bit life. It can be concluded that the maximum thrust force typically at least doubled during the number of holes studied. This increase was mainly constant for all feeds used. The maximum torque shown in Fig. 6 generally increases with increasing feed (with a few exceptions for the first holes drilled at higher feed) but is not strongly correlated to tool wear.

In Fig. 7, the maximum thrust force and torque produced while drilling a 2 mm double sample at different feeds and at different stages of the drill bit life can be seen. The maximum thrust force increases with feed and number of holes drilled (due to tool wear); however, this increase is not consistent for all feeds used. For lower feeds, the maximum thrust force increases only slightly due to tool wear, while for the higher feeds the thrust force doubled (as for the 2 mm sample). The max torque shown in Fig. 7 increased with

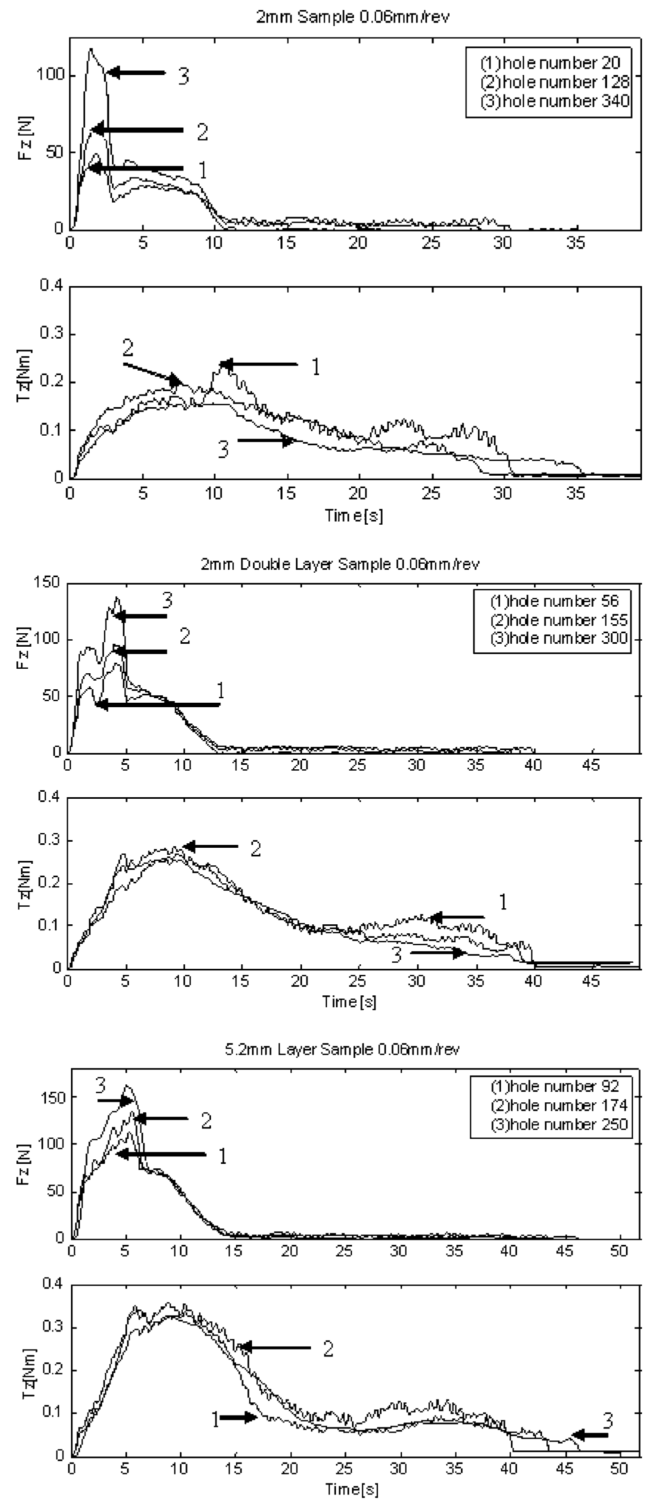

Fig. 5. Effect of tool wear on drilling thrust force and torque for various thicknesses.

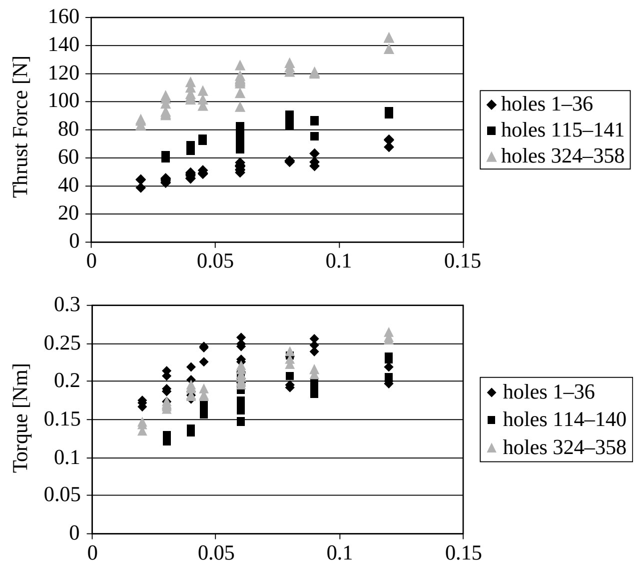

Fig. 6. Maximum thrust force and torque for different cutting speeds (2 mm sample).

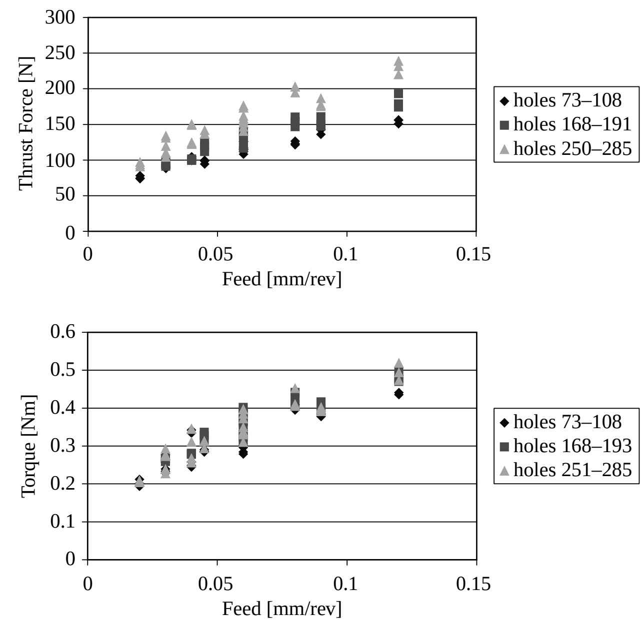

Fig. 8. Maximum thrust force and torque for different cutting speeds for 5.2 mm sample.

feed (again a few exceptions for the higher feeds) but did not relate to tool wear.

For the case of drilling a 5.2 mm sample, the results can be seen in Fig. 8. The thrust force increases with the feed used and with number of holes drilled. The influence of tool wear on the thrust force is more accentuated for higher feeds but not as much as when drilling thinner samples. The maximum torque was proportional to the feed used but was not affected by tool wear.

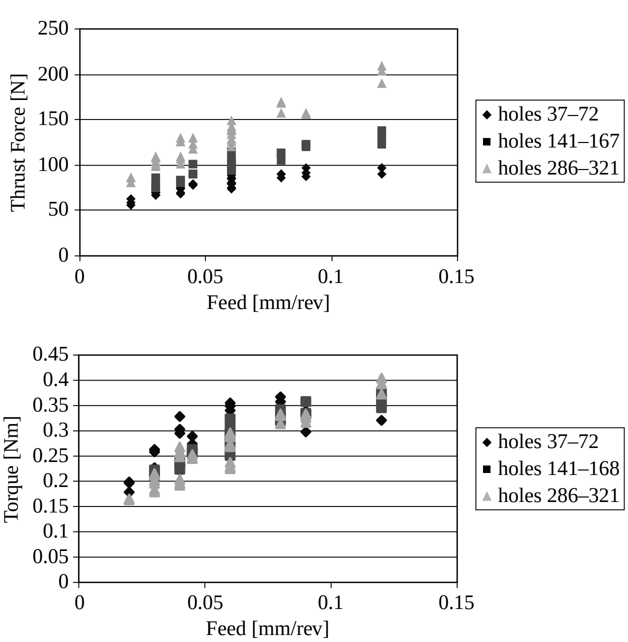

Fig. 7. Maximum thrust force and torque for different cutting speeds for 2 mm double layer sample.

5. Conclusions

The large number of experiments conducted show that the drilling process with the one shot drill can be modelled as a five step process with each step directly related physically to the various drilling and reaming processes. This was shown to be the case irrespective of the feed rates for different thicknesses of material and also for a two-layer stack. This model depends on the position of the drill bit in relation to the workpiece. It can also be concluded that the thrust force increases with number of holes drilled with a given drill bit, while torque is not particularly affected. It has been shown that the effect of tool wear on thrust force varies throughout the different stages, with the increase in thrust force being more noticeable just before breaking through. The thickness of the workpiece also plays a role on the effect of tool wear on the thrust force; the thinner the workpiece the bigger the increase of thrust force due to wear. The feeds used to drill also affect the increase of thrust force due to tool wear: the higher the feed the bigger the effect the tool wear will have on the thrust force produced by worn drill bits. Hence, thrust force and torque are a function of feed, drill bit, thickness of the workpiece, and tool wear (number of holes previously drilled). The findings of this paper enable the development of a mathematical model of the thrust force as described in part II of this paper. This model can then be used to extend and/or predict drill life and improve productivity and quality of hole drilling for industries such as aerospace, in which the drilling of composites is an important manufacturing process.

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