



On the temperatures developed in CFRP drilling using uncoated WC-Co tools Part I: Workpiece constituents, cutting speed and heat dissipation



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ARTICLE INFO

Article history:

Available online 20 December 2014

Keywords:

Carbon fibre
Thermosetting resin
Thermal properties
Heat dissipation
Drilling

ABSTRACT

This work investigated the influence of the material properties and cutting speed on the heat dissipation in the drilling of carbon fibre reinforced plastic (CFRP) composites using uncoated WC-Co tools. The first stage of the investigation compared the heat dissipation in drilling three different CFRP systems by measuring the temperatures developed at different distances around the borehole using thermocouples and an infra-red camera. The second stage studied the influence of cutting speed on the maximum temperatures developed in the workpiece in drilling a selected CFRP system in a cutting speed range from 50 to 200 m/min. The cross-linking density of the polymer matrix and the degree of crystallinity and structure of the carbon fibres exhibited a significant influence on the overall temperature and on the heat dissipation, whereas 150–200 m/min cutting speeds yielded higher concentration of heat, compared to 50–100 m/min cutting speeds.

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1. Introduction

The study of temperatures developed in the machining process of fibre reinforced plastics (FRP) composites has been of interest since FRPs became extensively used in the aerospace and automotive industries. A number of temperature acquisition methods used to measure and monitor different machining operations, comprising and combining experimental, numerical and analytical techniques, were studied and reported in the literature. The use of thermocouples embedded in the tool was the earliest and most common method used to measure the temperatures and the thermal gradients that occurred on the cutting edges of the selected tools during the machining process. In this method, thermocouples are embedded in the tool by machining adequate grooves and applying highly thermally conductive adhesives. Using small diameter thermocouples allows the temperatures developed along the cutting edge to be mapped. However, it is not possible to place thermocouples at the cutting edge, where the highest temperatures develop during the process [1,2]. Embedding thermocouples

in the rotating part of the system added complexity to the challenge of transmitting and recording the data.

Earlier studies set the tool as the static part of the drilling set-up and modified the workpiece to be attached to the spindle [3,4], however this arrangement allowed only one hole to be drilled at a time, making it difficult to reach a steady state temperature.

Another solution utilised wireless systems to transmit the data from the spindle in the machining of metals, alloys and CFRP composites [5,6]. The transmission system consisted of a special tool holder, which is formed by a radio frequency (RF) transmitter and an antenna. This system featured a high acquisition frequency (1 kHz) and a much reduced delay (150 µs). This wireless system provided good results, however considering that each tool requires individual preparation for its use in the RF system, the cost of the wireless tool holder makes this choice an expensive solution.

Other studies reported the choice of the dynamic thermocouple as an alternative method [1,2,7–9]. This technique utilises the tool and the workpiece forming a dynamic thermocouple, and requires previous characterisation and calibration of the system to relate the electromotive force to the developed temperatures. This method has been successfully applied in mapping the temperatures along the cutting edge in the drilling of aluminium [8] and monitoring the temperatures developed in CFRP milling [9]. However, the poor electrical conductivity of FRP composites

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complicates the preparation and characterisation of the dynamic thermocouple. A good number of authors considered the utilisation of non-contact and infra-red radiation techniques (pyrometers-optical fibres, optical infra-red radiation) to measure the temperatures developed in a number of machining operations [1,2,7,10–12]. These methods are limited to temperature acquisition and monitoring of uncovered surfaces and require calibration before their use to determine their emissivity and reflectivity, since the measurement is very sensitive to these parameters. However, infra-red cameras represent a fast and very accurate temperature measurement method.

Reported investigations studied the influence of the cutting parameters on the tool temperature in the drilling of CFRP laminates by embedding thermocouples in the tool [4,13,14]. Authors studied the influence of cutting speed in a 35–200 m/min range and reported an increased flank surface temperature with the increasing cutting speed. However, the study of the influence of feed rate (0.05–0.4 mm/rev range) on flank surface temperature yielded the contradicting results. Chen reported a decreased flank surface temperature with the increasing feed rate [13], whereas a more recent study by Weinert and Kempmann reported the contrary [4]. The different workpiece thicknesses (2 and 17 mm) and the experimental arrangement utilised in both investigations (workpiece as the rotatory element) could have prevented the tool from reaching a steady state temperature [14], thus explaining the difference in the reported results.

Tian and Cole reported the impact of the material constituents on the physical properties of CFRP composites. Both fibre volume fraction and direction exhibited significant influence on the in-plane and through thickness thermal conductivities of CFRP composites [11].

On the other hand, Knibbs and Morris reported that small misalignment of fibres in the composite showed to have limited influence on the thermal conductivity and significant impact on Young's modulus in the directions parallel to the reinforcement. However, thermal conductivity was affected to a greater extent in the transverse direction [15].

The type of fibres also showed to have significant impact on the thermal and mechanical properties of CFRP composites. Thermal conductivity and modulus of elasticity of CFRP composites having high modulus carbon fibre reinforcement exceeded that of high strength carbon fibres, which was attributed to the higher degree of crystallinity of the high modulus reinforcement [16,17].

The work presented in this investigation utilised two widely accepted temperature acquisition methods, data collection using thermocouples and thermal imaging (infra-red camera), to assess the impact that the material properties of selected CFRP systems (having different cross-linking densities and fibres crystallinity) and the cutting speed have on the maximum developed temperatures and on the heat dissipation in the drilling of CFRP composites.

2. Materials and methods

2.1. Composite systems

The CFRP plates used in this investigation were manufactured at the Composite Centre of the Advanced Manufacturing Research Centre with Boeing, The University of Sheffield. These plates were made from woven carbon fibre (CF) and epoxy prepreg plies having 55% fibre volume fraction (V_f), supplied by Cytec Engineered Materials. Initially, 350 × 350 mm plates were made by vacuum bag moulding method, laying up 42 prepreg plies (0° orientation laminate) to approximate thickness of 10 mm. Following the lay-up process, the plates were cured and post-cured in an autoclave, following the specifications provided by the manufacturer to develop

their full mechanical performance and the maximum glass transition temperature (T_g). Then, the plates were cut down to a size of 310 × 155 mm using a WardJet G-Series 5-axis water-jet CNC machine.

Three different CFRP systems were considered in this investigation:

- MTM44-1 and CF0300,
- MTM44-1 and CF2216, and
- MTM28B and CF0300.

MTM44-1 resin is a toughened phenol–formaldehyde (PF)-based aerospace grade resin, whereas MTM28B is a toughened epoxy DGEBA-based automotive grade resin. CF0300 is a 2/2 twill carbon fabric, 3 K high strength (HS) carbon fibre reinforcement, while CF2216 is a 2/2 twill carbon fabric, 6 K high modulus (HM) carbon fibre reinforcement, both having density of 199 g/cm³.

Dynamic mechanical analysis (DMA) and thermo-mechanical analysis (TMA) techniques were utilised to measure the glass transition temperature (T_g) and coefficient of thermal expansion (CTE) of MTM44-1 and MTM28B resins. The DMA device utilised to study the glass transition temperature of the selected resins was a *Metra-viv VA2000 ViscoAnalyseur* using a 3-point bend configuration. The specimens were tested in a single-frequency mode (10 Hz), applying static and dynamic displacements of –80 µm and 50 µm respectively and performing temperature sweeps ranging from room temperature to 160 °C (MTM28B) and 250 °C (MTM44-1) at a 3 °C/min heating rate. Coefficients of thermal expansion were measured utilising a *Perkin Elmer Diamond TMA* applying a force of 10 mN and performing temperature sweeps ranging from 35 °C to 160 °C (MTM28B) and 250 °C (MTM44-1) at a 5 °C/min heating rate.

2.2. Drilling tool

The main tool used in this investigation was ø6.35 mm two flute double angle WC-10%Co uncoated Sandvik Coromant's CoroDrill 856 drill bit. The main geometry features of this tool are 120° and 40° point angles (chamfered geometry), 25° helix angle, 12° primary clearance angle, 20° secondary clearance angle and 0.64 mm margin width. All the drill bits used in this investigation were manufactured in the same batch, having a maximum lip height variation of 25 µm, a maximum web eccentricity of 100 µm and a chisel edge centrality of 0.05 mm. The tool utilised to prepare the plate to embed the thermocouples was ø1.25 mm uncoated tungsten carbide Sandvik Coromant's CoroDrill 840 drill bit. The CNC machine utilised was a three-axis DMG DMU 60monoBLOCK fitted with Sandvik Coromant's CoroChuck 930 hydraulic tool holder, having a total measured run-out of 12 µm. All the machining operations in this work were conducted without coolant (dry drilling).

2.3. Thermocouples

This investigation utilised Perfluoro Alkoxy Alkene (PFA)-insulated type K fine-gauge (chromel–alumel) thermocouples manufactured and supplied by Omega Engineering, having a working temperature range from –200 °C to +1300 °C, 1 m long, ø0.25 mm wire and ø0.49 mm bead. According to the specifications provided by the manufacturer, the utilised thermocouples feature a response time (defined as the required time for the thermocouples to acquire 63.2% of their final temperature when the bead is alternately exposed to two different temperatures) of 0.22 s, measured with exposures between 93 °C and 38 °C in still water. A Pico Technology's TC-08 Thermocouples Data Logger, featuring 8-channels and automatic cold junction compensation, and Pico Log

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