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Full Length Article

Effects of atomization-based cutting fluid sprays in milling of carbon fiber reinforced polymer composite

Tarek Elgnemi[a], Keivan Ahmadi[a], Victor Songmene[b], Jungsoo Nam[c], Martin B.G. Jun[c,*]

[a] Department of Mechanical Engineering, University of Victoria, Victoria, BC, Canada
[b] Department of Mechanical Engineering, ETS, Montréal, QC, Canada
[c] Department of Mechanical Engineering, Purdue University, West Lafayette, IN, USA

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ABSTRACT

Carbon Fiber Reinforced Polymers (CFRP) are considered hard to cut materials, because of the abrasiveness of carbon fibers and the low transverse strength of the composite layers that leads to delimitation under machining forces. The application of cutting fluid is a common way of reducing tool wear and machining forces in machining of metallic materials, yet this solution cannot be applied in machining of CFRP, because moisture damages the structural integrity of the composite workpiece. In this paper, an experimental study is conducted to examine the feasibility and effectiveness of applying atomized cutting fluid in milling of CFRP. In the studied atomization-based method, the cutting fluid is broken down into micrometer size droplets that are sprayed directly into the cutting zone. In the presented study, two types of cutting fluids, general purpose semisynthetic coolant and vegetable oil, are applied by atomization, and their performances in reducing cutting forces, tool wear, surface roughness, and delamination are studied over a range of cutting speeds and feed rate values.

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP) offer a higher strength to weight ratio and superior corrosion and fatigue resistance compared to traditional metals. Mechanical machining processes such as milling and drilling are usually a critical part of the assembly and finishing stage of producing CFRP parts in a wide range of applications such as aerospace, automotive, and biomedical devices. The machinability of CFRP materials is limited by the excessive tool wear due to the abrasiveness of carbon fibers, and by the machining induced damages such as delamination that is caused by the low interlaminar strength of composite layers [1–4]. The application of cutting fluid is a common solution for increasing the tool life and reducing cutting forces in the machining of metallic materials. Cutting fluid dissipates the generated heat and reduces the friction between the chip and the cutting edge, and consequently lowers the tool wear, reduces cutting forces, and improves the extent of machining induced damages [5,6]. Nevertheless, the application of cutting fluid in the machining of CFRP is not common, because moisture damages the structural integrity of CFRP [7]. Devising a cutting fluid application method that provides the lubricating and cooling effects of the cutting fluid without it being absorbed into the material could significantly improve the tool life and reduce cutting forces in the machining of CFRP. In addition, the application of cutting fluid could reduce the level of the dust and airborne contaminations that are dispersed into the shop environment and cause hazard to the health of the operator, and damage the machine tools.

Atomization-based cutting fluid application has been studied as an effective method of cooling and lubricating the cutting zone in several applications such as micromachining [8–10]. In this method, the atomized cutting fluid is sprayed directly into the cutting zone to lubricate the chip and tool interface, and also to dissipate the generate heat by fast evaporation. Because of the significantly higher evaporation rate of the atomized cutting fluid, the applied coolant does not absorb into the workpiece material. Therefore, atomization of the cutting fluid may provide a viable method for applying cutting fluid in CFRP cutting.

In this paper, the effectiveness of atomization based cutting fluid application in improving the machinability of CFRP is studied experimentally. CFRP milling operations are conducted in a range of cutting speed and feed rate values in dry condition, and using two types of cutting fluids, a general purpose semisynthetic coolant and vegetable-oil-based coolant as a sustainable alternative

* Corresponding author.
E-mail address: mbgjun@purdue.edu (M.B.G. Jun).

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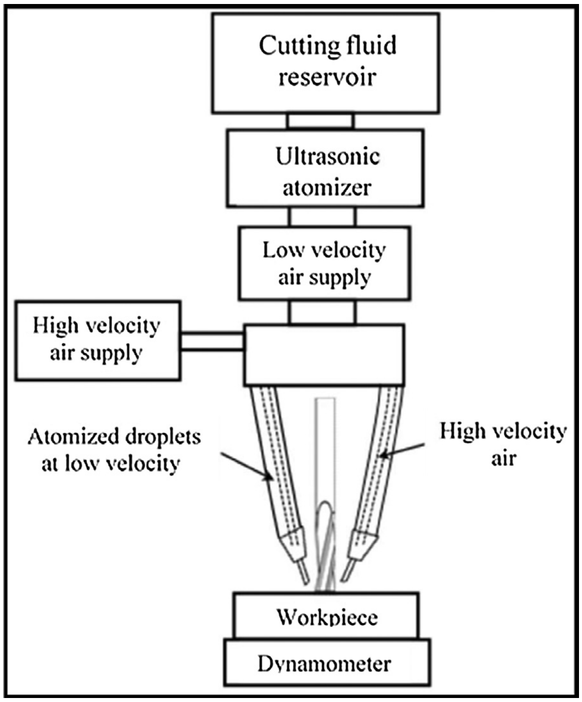

Fig. 1. A schematic design of the atomization-based cutting fluid application system.

to conventional coolants. The resulting cutting forces, tool wear, surface roughness, and delamination are measured to study the machinability of CFRP in each test.

In the next section, a brief description of the atomization-based cutting fluid application system is provided. In Section three, the experimental setup and the design of experiments are described. The measured cutting forces, tool wear, surface roughness, and delamination are discussed in Section four.

2. Atomization-based cutting fluid spray system

A schematic of the cutting fluid application system that is used in this study is shown in Fig. 1. This system is similar to the atomization setup that was used in [10]. An experimental evaluation of an atomization-based cutting fluid application system for micromachining. A brief description of the atomization-based cutting fluid application system is presented in this section; more details are available in. An experimental evaluation of an atomization-based cutting fluid application system for micromachining]. As shown in Fig. 1, the ultrasonic vibrations of the piezoelectric actuator breaks down the cutting fluid that is stored in the reservoir into micrometer diameter droplets. The atomized cutting fluid is carried through the fluid application pipe with the aid of a low velocity air. A small diameter pipe that lies inside the coolant pipe delivers the high-pressure air to the tip of the coolant pipe to spray the atomized fluid into the cutting zone.

3. CFRP milling experiments

3.1. Experimental setup and conditions

The experimental setup is shown in Fig. 2. The nozzle is directed to the cutting zone, so that the spray jet effectively wets and cools the cutting zone and simultaneously flushes away chips. Milling experiments were performed using a custom built machine tool (Alio Industries). The machine tool is equipped with a NSK E800Z spindle with maximum applicable speed of 80,000 rev/min. Two-fluted flat end mills of 3.175 mm in diameter are used for milling operations. The dimensions of the end mill are shown in Table 1. Cutting forces are measured using a Kistler MiniDyn 9256C1 dynamometer. The measured cutting force signals were digitized and transferred to the computer using a NI PCI-6133 data acquisition board. The shape of the generated chips, quality of machined surface, and delamination formations are evaluated using an optical microscope (Olympus BXFM) and a Scanning Electron Microscopy (SEM, Hitachi S4700).

To study the effectiveness of applying atomized coolant, the experiments were carried out in dry condition and using two types of cutting fluid: (a) general-purpose multi-metal (TRIM®) SC520 cutting fluids and (b) Canola vegetable oil. In both cases, the cutting fluid was diluted to 5% in volume by adding distilled water in the atomizer's reservoir. The atomized droplets are carried through the tube of 25.4 mm diameter and the air jet pipe has an inner diameter of 1.6 mm. The ultrasonic atomizer is a 22.0 mm diameter piezo transducer at 1 MHz For droplets generated by ultrasonic atomization, the droplet size generally depends on the frequency of ultrasonic vibration and fluid properties. The average droplet size of Canola vegetable oil around 2.1 μm. For comparison, conventional (TRIM®) SC520 mixed at 5% with water is also observed under an optical microscope and the size of oil droplets seems to be similar to that of canola oil droplets emulsified in water [10]. Multi-layer CFRP sheets of 1.56 mm (1/16 in) thickness were milled in each experiment. Each CFRP sheet consists of four unidirectional tapes of equal thickness that are laid up in (0F/90/0F/90/0F/90/0F/90) configuration as shown in Fig. 2. The approximate fiber volume in each tape is 54%. The Young's modulus of the fibers was estimated at 225GPa and the Young' modulus of the sheets was estimated at 65GPa.

3.2. Design of experiments

The effect of various machining parameters and cooling methods on the machinability of CFRP is studied by conducting a full factorial experimental design. The three machining parameters that are studied include a) feed rate, b) cutting speed, and c) cooling method. Three feed rate levels (2, 4, and 6 micrometers/tooth), two cutting speed levels (20,000 and 40,000 rev/min), and three cooling methods (dry, conventional coolant, and vegetable oil) were examined in the experiments. A full factorial design of experiments across the three factors of feed, speed, and cooling type, and their corresponding levels require $3 \times 2 \text{x } 3 = 18$ experiments. The cutting conditions in each of the 18 experiments are listed in Table 2. In each of the experiments, a new tool was used and eight slots of 18 mm length were cut with full-immersion milling. The axial depth of cut was 0.3 mm in all of the experiments.

Table 1
Tool specification.

Cutting diameter	Flute length	Shank diameter	Overall length	Rake angle	clearance angle
3.175 mm	6.35 mm	3.175 mm	38.1 mm	7°	30°