International Journal of Machine Tools & Manufacture 118–119 (2017) 12–25

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Towards understanding the cutting and fracture mechanism in Ceramic Matrix Composites

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ARTICLE INFO

2015 MSC:
00-01
99-00

Keywords:
Machining
Ceramic Matrix Composites
Orthogonal cutting
Fracture mechanism
Crack formation

ABSTRACT

Ceramic Matrix Composites (CMCs) are increasingly used for the manufacture of high-value parts for several industries such as the aerospace, nuclear and automotive. Nevertheless, their heterogenic, anisotropic and brittle nature make difficult to characterise the machining process and therefore, an in-depth understanding of the cutting mechanics is needed. In this regard, this paper aims to understand the different behaviours of CMCs while employing orthogonal cutting. The first part of this article proposes a novel theoretical approach to explain the different types of cutting behaviours (fracture and shear cutting) based on the inelastic and orthotropic properties of the CMC's by using a high imaging system and measuring the cutting forces. The second part aims to understand the cutting and fracture mechanism by developing for the first time a specific analytical model for each of the three main orthotropic orientations, defined by the three main relative fibre orientations respect to the feed direction, which are found in cutting of CMCs. This is approached by the calculation of the specific cutting energy needed to fracture the CMC's during cutting (energy release rate, G_c) using fracture mechanics and cutting theories. This analytical model has been successfully validated for a Carbon/Carbon composite with the experimental data obtained for the brittle cutting and by introducing the concept of a rising R-curve in cutting models. Moreover, comparing the results obtained for the energy release rate for the brittle and semi-ductile mode, it is observed that the material experiences an important change in the energy release rate according to the brittle-to-semi-ductile transition occurring while reducing the depth of cut. Finally, a novel monitoring method based on the vibrations of the sample has been found successful to understand the type of crack formation appearing while cutting CMCs.

1. Introduction

1.1. Ceramic Matrix Composites (CMCs)

Composite materials have increased in demand in many different industries because of their excellent mechanical characteristics such as the strength-to-weight, stiffness-to-weight, corrosion and fatigue resistance. Composites are formed from two or more materials, resulting in properties that can not be achieved with monolithic materials. Commonly, one of the materials acts as a matrix and the other one as a reinforcement. The matrix is in charge of spreading the stress to the fibres and protecting them from external damages while providing the final shape of the component. On the other hand, the reinforcement provides greater mechanical properties [1].

Depending on the type of reinforcement, composite materials are classified in particulate, flake and fibre composites [2]. Fibre composite can also be classified as short or long fibres. Short fibres slightly increase the properties of the matrix randomly in all directions, while long fibres highly increase the properties in specific directions. In aerospace applications, long fibre composites are consistently used in order to reduce weight by just having preferential directions with high mechanical properties. Composite materials can also be classified depending on the nature of the matrix: Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs) [1,3]. PMCs are often refereed as FRP (Fibre Reinforced Polymer) and have a polymeric matrix (i.e. Epoxy or Phenolic) reinforced with brittle fibres (i.e. Carbon or Glass). These materials are being chosen as a replacement of light metal alloys such as those based on aluminium or titanium. MMCs are used for applications requiring higher temperature in service than the PMCs and the most common structure are Boron or Silicon-Carbide fibres embedded in a metal matrix (i.e. Titanium or Steel) [1].

Ceramic Matrix Composites have been the preferred candidate for the replacement of some elevated temperature materials in the modern industries. In aerospace, CMCs have been introduced in gas turbine engines as a replacement of some superalloys [4] and in rocket nozzles

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http://dx.doi.org/10.1016/j.ijmachtools.2017.03.008
Received 22 December 2016; Received in revised form 27 March 2017; Accepted 29 March 2017

[5]. For nuclear applications, CMCs are under consideration to be used as a structural material for fusion and fission reactors [6]. CMCs have also been employed in frictional applications as braking systems in cars or aircrafts [1]. The CMC's success in extremes applications is due to their high mechanical and chemical performances at high temperature, such as fatigue and oxidation resistance [4]. Moreover, compared to the monolithic ceramics, the reinforcement in CMCs displays improved fracture toughness and mechanical strength. A common CMC material used in a wide range of industrial applications is the Carbon/Carbon (C/C) in which high strength carbon fibres are embedded in a graphite matrix. This combination makes the C/C an excellent candidate for ultra-high specific strength applications. Further reinforced ceramics found in the aerospace industry are the C/SiC and SiC/SiC where Carbon or Silicon Carbide fibres are inserted in a Silicon Carbide matrix which possesses better corrosion resistance than Carbon [7]. Due to this growing demand on CMCs, fundamental orthogonal cutting tests are needed for a better understanding of the machining process.

1.2. Orthogonal cutting in composite materials

In so-called orthogonal cutting, a single cutting edge wider than the work-piece is used to unidirectionally cut along the surface. The cutting is assumed to be uniform along the cutting edge, reducing the problem into a two-dimensional scenario [8]. The cutting mechanism in composite materials has been analytically and experimentally investigated using orthogonal cutting. Pwu and Hocheng [9] analysed the cut quality in unidirectional composites by modelling the chip length and the fracture mechanism. The model considered orthotropic behaviour and beam theories to understand the chip formation but only considered fibres placed perpendicularly to the cutting edge. Sahraie Jahromi and Bahr [10] proposed an analytical model to calculate the cutting forces applying bending theories on single fibres and extrapolating to the whole composite by using the fibre volume fraction. Nevertheless, the model was only developed for one specific fibre orientation with simulated results showing some discrepancies with some experimental data. Bhatnagar et al. [11] correlated the cutting force with the shear properties of composite materials for different fibre orientations and proposed an empirical relation to calculate the cutting force. However, the mechanics of the system were not modelled and therefore, the empirical solution has limitations in model applicability for other types of composites such as the CMCs. Wang and Zhang [12] studied the surface quality of unidirectional composites by evaluating the influence of different rake angles and fibre orientations; while this is useful information, the aspects of different cutting and fracturing modes depending on the depth and width of cut were not considered. Moreover, several Finite Element Models (FEM) using cohesive theories, elasto-plastic behaviour and fracture mechanisms were studied to predict the cutting forces for different fibre orientations [13–15]. While this work can provide useful specific data, an analytical model might offer a better understanding of the parameters and materials properties affecting the cutting mechanism.

Furthermore, all these models have been proposed for PMCs or MMCs where a ductile cut formation is clearly predominant. In contrast with these, in CMCs a transition between semi-ductile to brittle cutting can often be found, affecting the surface damage created by the crack propagation. In this respect, as the CMCs possess a brittle matrix, it could be commented that considering its different mechanical behaviours under cutting was a novel commitment necessary for the understanding of the cutting process.

1.3. Fracture mechanics in cutting

Fracture mechanics has been used to some extent in orthogonal cutting by considering the notion of fracture toughness for the understanding of the crack generation [8,16]. Patel et al. [17] and Wang et al. [18] used orthogonal cutting as a method to calculate some materials properties such as the fracture toughness and the yield stress in isotropic materials such as metals and polymers. Liao and Axinte [19] used fracture mechanics to predict the chip formation mechanism in cortical bones, also considered as a composite structure. Nonetheless, the mechanical approach for the three cutting orientations used (longitudinal, across and transverse) was simplified into one final analytical expression, loosing accuracy on the explanation of the mechanical behaviour. Theoretical approaches for chip formation in isotropic materials have been proposed to understand the bending and rotation mechanism that chips can suffer in cutting and in peel-up tests [20]. However, due to the isotropy of the materials tested, an anisotropic behaviour on the fracture toughness and therefore of the cutting mechanism was not considered.

Some researchers have been interested in the so-called ductile-to-brittle transition that specially brittle materials can experience during the machining at relative low uncut chip thickness. It has been commented [21]; that, depending on the specific cutting energy, the machining can be accomplished by plastic deformation (ductile behaviour) or by crack propagation (brittle behaviour). The comprehension of this transition point is a key factor for the understanding of the material cracking and therefore, the workpiece surface quality in machining brittle materials [22]. Nevertheless, further research has not been documented in the interpretation of the ductile-to-brittle transition between cutting modes in composites materials such as CMCs where due to their brittle matrix, this phenomenon can occur at low uncut chip thickness. Commonly CMCs are manufactured with long reinforcing fibres creating three mutually perpendicular planes of material symmetry. This implies that the elastic material properties are defined by nine coefficients and therefore, CMCs are not completely anisotropic but they are termed orthotropic [2].

In an attempt to fill the research gaps related to cutting orthotropic materials that can display ductile-to-brittle behaviour, e.g CMCs, this paper aims to propose a mechanism to interpret the cutting and fracture behaviour for each of the three main orthotropic orientations. In this respect, an analytical cutting model based on the inelastic behaviour and fracture mechanics of orthotropic brittle composite materials is proposed for the understanding of the surface quality and integrity in machining. The model has been validated experimentally by analysing the machining forces, cracks behaviour, vibrations and surface damages. This work might be an interesting lead for further research in other traditional machining process such as drilling, milling or turning for CMCs and similar materials.

2. Experimental methodology

To study the cutting mechanism in CMCs, orthogonal tests with different fibre orientations have been performed to observe the response of the brittle matrix-composite and obtain unique data (e.g. forces, vibrations and crack formation mechanisms) not previously found in the literature and needed for the validation of the analytical approaches.

Samples (25×3×5 mm) of bidirectional Carbon-Carbon with an approximate Young Modulus along the fibre direction of 80 GPa and 5 GPa out of the fibres direction, have been water-jet cut. Afterwards, the samples have been carefully polished to achieve the final dimensions and glued with a structural epoxy resin to an aluminium plate in order to have greater clamping surface and to avoid any induced damage in the composite structure.

An in-house developed 4-axis miniature machine tool [23], with a repeatability of 0.1 µm of the positioning stage, was adapted for performing orthogonal cutting tests. A solid carbide cutting edge with rake angle α=8°, clearance angle γ=8° and edge radius r=5 µm was used as previously done in [19]. In order to reduce the friction force and therefore to meet the setup recommended for orthogonal cutting, the width of the sample was thinner than the width of the cutting edge (2 mm). The cutting speed chosen for the trials was 30 mm/min since