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Brittle damage and interlaminar decohesion in orthogonal micromachining of pyrolytic carbon

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A B S T R A C T

Engineered features on pyrolytic carbon (PyC) have been reported to improve the functional performance of the cardiovascular implants. PyC also finds application in thermonuclear components due to its unique directional thermal properties. Note that PyC comprises of stacked layers of brittle graphite-like material and its machining characteristics differ from plastically deformable isotropic materials due to brittle damage and interlaminar decohesion. Consequently, this study is aimed at understanding the mechanics of material removal in the plane of transverse isotropy (horizontally stacked laminae) of PyC via a finite element model. A damaged plasticity material model has been used to capture the effect of material degradation of a brittle material under machining. Uniaxial tension/compression tests have been carried out to calibrate the damaged plasticity model. A surface based cohesive bonding has been used between the layers to simulate the interlaminar decohesion which results in peeling, slipping and delamination during machining. The model predicts the cutting force and thrust forces under different process conditions. The cutting force predictions from the finite element model have been validated against the experimental data for different cutting conditions. In addition, the model also predicts the chip morphology for different machining conditions. The prediction error in the model lies between 2% and 23%. Parametric studies have also been performed to understand the effect of the machining parameters, such as rake angle, uncut chip thickness on the process response. It is found that use of the positive rake angle decreases the cutting forces up to 72%.

1. Introduction

Pyrolytic carbon (PyC) is a material known for its excellent biocompatibility, high strength-to-weight ratio and unique directional thermal properties which finds application in biomedical implants and thermal sinks. It has layers of brittle graphite-like material as shown in Fig. 1 [1]. The layered AB plane is the plane of transverse isotropy and the C plane is anisotropic. Mechanical Micromachining can be used to create functional features in PyC. However, with notable exceptions of few experimental studies [1–3], most of the experimental and modeling work reported in the literature on mechanical micromachining (micromilling, microturning, etc.) is for isotropic, homogeneous, and plastically deforming metals [4–7].

To the best of authors' knowledge, no work has been reported on the modeling of micromachining process for layered brittle materials. Due to the layered and anisotropic nature of PyC, the machining characteristics are significantly different from the conventional isotropic materials. The material separation phenomenon in micromachining of PyC has yet to be fully understood. During the orthogonal micromachining of PyC, the chip layer is peeled and the chip failure occurs due to tension in the bottom portion and compression in the top portion. This tension compression results in delamination of the layers in the chip. Note that the brittle materials degrade under mechanical loading. The degradation phenomenon can be captured via a damaged plasticity model wherein the stiffness of the material deteriorates as a function of strain [8]. The chip formation mechanism uses traction separation law for interlaminar decohesion which captures the peeling, slipping and delamination in the layered chip. The damaged plasticity model is used for capturing the tensile and compressive behavior of the degraded material. Uniaxial tension and compression tests are required for calibrating the parameters of the damage model. Finally, a finite element model for orthogonal cutting in AB plane (plane of transverse isotropy) is developed based on damaged plasticity and traction separation to understand the material removal mechanism in PyC. The proposed model has been validated with orthogonal micromachining experiments for cutting forces and chip morphology. To characterize the effect of machining conditions, a parametric study has been performed to study the effect of depth of cut, tool width, rake angle and cutting speed on the brittle failure and the

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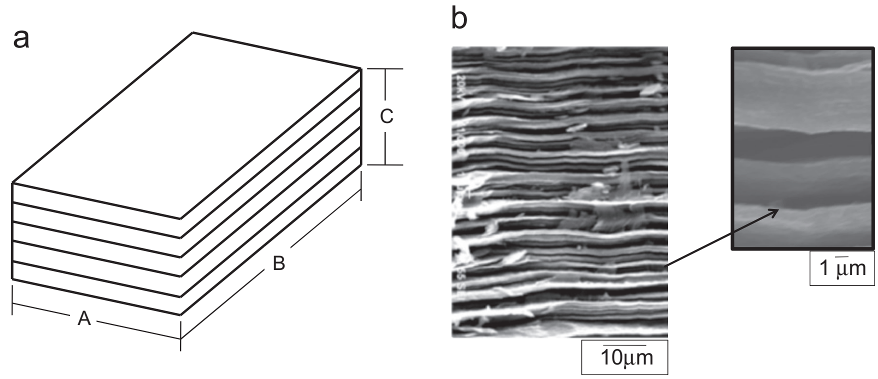

Fig. 1. Schematic and SEM image of PyC [1].

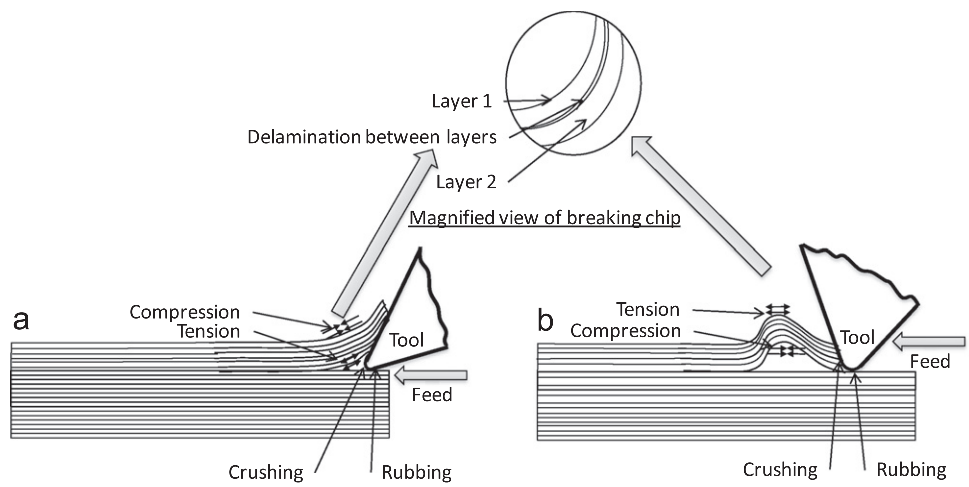

Fig. 2. Schematic of chip formation mechanisms: (a) peeling and bending in positive rake angle; (b) slipping, bending and crushing in negative rake angle.

interlaminar decohesion which affects the cutting forces and chip morphology.

2. Physical description of the micromachining process in PyC

In the orthogonal micromachining of PyC in the plane of transverse isotropy, the following mechanisms take place: peeling, slipping, delamination, bending rubbing and ploughing/crushing. Figs. 2(a) and (b) show the mechanism of the chip formation for positive and negative rake angles, respectively.

Peeling and slipping occur in the between the two laminae close to the tool tip due to interlaminar decohesion. The interlaminar peeling/slipping depends upon the magnitude of the traction force in the cutting and thrust directions and the rake angle. As shown in Fig. 2(a), the bending stresses are generated in the chip due to the peeling of the layer while cutting with a positive rake angle tool. The bending of the chip induces compression in the top and tension in the bottom section. Fig. 2(b) shows cutting with a negative rake angle which results in the slipping of the chip. Contrary to the peeling mechanism, the tensile stresses are induced in the upper section and the compressive in the lower section of the layer. These stresses eventually lead to the material separation. The above two cases result in the delamination of the chip during bending, magnified view of Fig. 2 shows chip delamination.

A finite element model capturing the abovementioned phenomena could enhance the understanding of micromachining process mechanism of layered brittle materials. The proposed model considers the effects of tool nose radius and rake angle on the cutting forces and chip morphology. Note that the negative rake angle induces significant amount of crushing due to the brittle nature of PyC. The ploughing phenomenon observed in the plastically flowing material is replaced by crushing. The rubbing between the flank and workpiece has also been modeled.

3. Material characterization

3.1. Mechanical properties

Pyrolytic carbon is a layered anisotropic material produced by the decomposition of hydrocarbon gases. A layered structure makes it stronger in certain orientations. Some of the mechanical properties of PyC used in the simulations have been taken from the material datasheet [13]. Flexural strength and fracture toughness (for different orientations) have been characterized and reported in the literature [9–12]. As mentioned previously, the damaged plasticity material model needs postfailure behavior of the material under uniaxial tension and compression, which has not been reported in the literature. Hence, a number of tests were conducted on the material. The stacked layers of the material and the cohesive bonding have been modeled separately in the proposed model. The mechanical properties of a single layer are required to simulate the machining response of the stacked laminae. The layered material is tested under tension and compression to estimate the properties of a single layer.

3.2. Material testing under uniaxial tension and compression

The damaged plasticity model requires material response under the elastic limit as well as the postfailure response beyond