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Analytical model to determine the critical conditions for the modes of material removal in the milling process of brittle material

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ABSTRACT

Brittle materials are prone to cleavage-based fracture during machining. In conventional scale machining of brittle material, crack-propagation is the dominant mechanism of material removal which results in a degraded machined surface. The challenge is to perform machining of brittle material such that the material removal occurs predominantly by chip formation rather than the characteristic brittle fracture. In this case, a high quality finish is achieved on the machined surface. Ductile-mode machining has emerged as a promising technique to finish a crack-free machined surface on macroscopically brittle materials. In the past, ductile-mode machining has mostly been performed by single-edge cutting process. This paper outlines an analytical model to determine the critical conditions for finishing a crack-free surface on brittle material by milling process. Four distinct modes of machining have been identified in the milling process of brittle material. In this model, the critical conditions for different modes of machining have been determined with respect to the relationship between the radial depth of cut and the depth of subsurface damage caused by the brittle fracture during machining. Verification tests were performed on tungsten carbide workpiece and the experimental results have validated the proposed machining model. It has been established that if the radial depth of cut is greater than the subsurface-damage depth in the milling process of brittle material, it is possible to finish a crack-free machined surface by removal of material through a combination of plastic deformation and brittle fracture. However, if the radial depth of cut is less than the subsurface damage depth, brittle fracture must be prevented in ductile-mode milling to finish a crack-free machined surface.

1. Introduction

Brittle materials undergo cleavage-based fracture in conventional machining process due to their low fracture toughness. The fracture originated from cleavage appears on the machined surface resulting in the degraded surface finish. But under controlled set of cutting conditions, cleavage or brittle fracture is suppressed and material can be removed by chip formation in machining of a typically brittle material. This kind of machining process is known as ductile-mode machining. Blackley and Scattergood (1991) reported that if feedrate is maintained below a critical value, ductile-mode machining of brittle material can be achieved by single-edge cutting process. It is believed that if the undeformed chip thickness is below a certain limit, energy required to cause brittle fracture is higher than the energy required to cause plastic deformation and hence plastic deformation becomes the dominant mechanism of material removal in machining of a brittle material (Fang and Zhang, 2004). Patten et al. (2005) suggested that high pressure phase-transformation is responsible for plastic response in ductile-mode machining of ceramics. Bifano et al. (1991) proposed a model which established that critical depth of cut for ductile–brittle transition is a function of intrinsic properties of the workpiece material governing brittle fracture and plastic deformation. Moriwaki et al. (1992) established that critical uncut chip thickness for ductile–brittle transition can be increased significantly by applying ultrasonic vibrations during machining of brittle material. Cai et al. (2007) reported that to achieve ductile-mode machining of brittle material, the undeformed chip thickness must be less than the cutting edge radius and cutting edge radius must be less than a certain limit. This in essence provides an effective rake angle that is highly negative leading to high compressive stresses in the cutting zone which suppress the crack-propagation in ductile-mode machining (Fang and Chen, 2000). The upper-bound limit of cutting edge radius for ductile-mode machining was found to be at submicron scale for extremely brittle materials such as silicon and at microscale for comparatively less brittle material such as tungsten carbide (Arefin et al., 2007).

Due to material removal by plastic deformation, ductile-mode machining yields a superior surface finish on brittle materials without requiring any secondary finishing process. Schinker (1991)

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established that in ductile machining of brittle material, quality of machined surface depends on several factors such as subsurface residual stresses, micro-shear bands and micro-ripple pattern and different types of micro-cracks, which are governed by glass type, cutting speed, depth of cut, cutting edge geometry and environmental conditions. Fang and Chen (2000) reported that surface finish of workpiece in ductile-mode machining is heavily influenced by tool-edge sharpness. Shibata et al. (1996) proposed a model based on slip orientation factor to predict the surface features machined along different crystallographic orientations of single-crystal silicon.

Mostly brittle materials are subjected to abrasive based finishing processes to achieve polished surface on the machined surface. Due to generation of superior finish, ductile-mode machining can replace these abrasive processes in certain applications.

Tungsten carbide is a very hard and brittle material. It is very sensitive to the surface cracks and defects especially under fatigue conditions. High quality surface-finish is therefore desired on precision components made of tungsten carbide. Tungsten carbide products are typically fabricated by powder metallurgy technology. Diamond grinding and polishing are applied to achieve required level of surface finish. But polishing process has low productivity level and results in high production cost. Furthermore, such finishing processes require specialized equipment which means capital cost is too high if few parts or small batch of tungsten carbide parts is desired. Machining process, being flexible and versatile, is very suitable for low volume production. It is therefore desired to apply tool-based mechanical micromachining process for manufacturing discrete parts from tungsten carbide with improved surface finish. However, it is not easy to machine tungsten carbide by traditional machining process due to its poor machineability. It is also prone to brittle fracture during machining like other brittle materials. The certain machining conditions must be maintained during ductile-mode machining of tungsten carbide to avoid brittle fracture. Some studies have been made by the authors on ductile-mode machining of tungsten carbide. Liu and Li (2001) presented an energy based model to determine critical chip thickness for ductile-mode machining of tungsten carbide. They reported that critical chip thickness was at micrometer scale for cutting tungsten carbide in ductile-mode. Liu et al. (2004) also suggested that material can be removed by chip formation in machining of tungsten carbide to achieve nanometric finish for rapid production of prototypes. Single crystal diamond tool is not preferred for machining tungsten carbide due to its short life and high cost (Suzuki et al., 2007). Chandra et al. (2009) reported that polycrystalline diamond (PCD) is efficient tool material for achieving improved finish on tungsten carbide. The machining in all these studies has been performed by single-edge cutting process. It is difficult to machine complex features on the workpiece by single-edge process. The use of milling process for ductile-mode machining is inevitable to machine more complex profiles and features on brittle materials rapidly.

Ductile-mode milling process is relatively less explored process. Few studies have reported the ductile-mode milling. Matsumura et al. (2006) reported ball-end milling process of tungsten carbide and established that micro features on tungsten carbide workpiece can be machined by ball-end milling. The authors have already reported that feed per tooth is the critical parameter in ductile-mode milling to achieve a crack-free machined surface (Arif et al., 2011a). Foya et al. (2009) investigated the influence of inclination angle of tool on ductile–brittle transition in ball-end milling of glass. However, very less theoretical and analytical work has been reported on ductile-mode milling. Therefore, an analytical study is desired to model the possible regimes of machining under broad range of cutting conditions to further analyze the machining parameters which determine the maximum permissible material removal rate in ductile-mode milling. This study is expected to meet such technology gap for ductile-mode milling. Since the material removal in ductile-mode must be below a critical threshold dictated by certain processing parameters, it is of paramount importance to formulate a comprehensive analytical model to quantify these critical parameters.

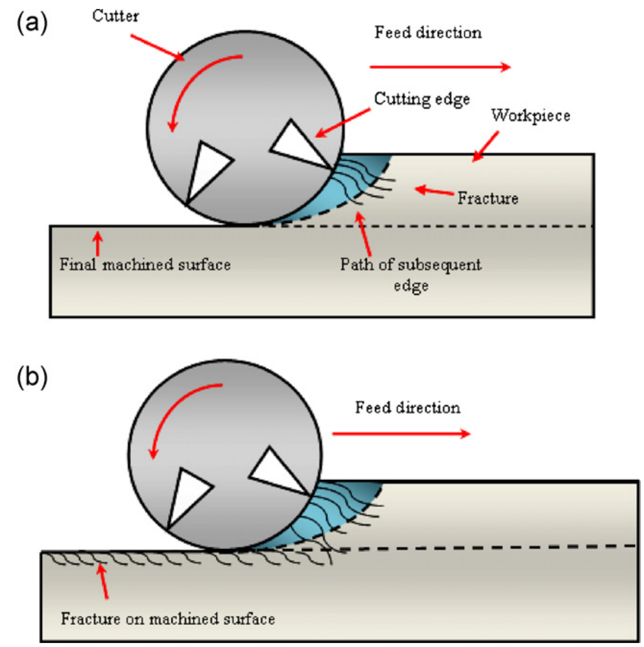

Fig. 1. Upmilling process at (a) low feed per tooth and (b) high feed per tooth (Arif et al., 2011a).

The specific objective of this study is to present an in-depth analytical machining model and its experimental validation for various modes of material removal in milling process of brittle materials. The determination of the critical conditions in terms of feed per tooth is attempted by a criterion based on the relationship between the radial depth of cut and the subsurface damage depth due to brittle fracture in milling process of brittle material.

2. Theoretical analysis

2.1. Milling of brittle materials

In peripheral milling process with up-milling cut, if the increasing value of undeformed chip thickness reaches the critical value, brittle fracture takes place at that point in the cut. If the brittle fracture point is sufficiently far above the plane of final machined surface, the fractured portion is removed by the cutting action of the subsequent edge as shown in Fig. 1(a). In case the brittle fracture point is too close to the plane of final machined surface, the subsequent edge cannot remove the fractured zone and final machined surface has brittle fracture on it as shown in Fig. 1(b). The height of brittle fracture point is controlled by the feed per tooth. A lower feed per tooth decreases the rate of increase in undeformed chip thickness in the cut causing the brittle fracture point to move upwards from the plane of final machined surface. The details on such cutting mechanism can be found in the study reported by the authors (Arif et al., 2011a).

2.2. Development of cutting strategy

Let us assume f_c is the highest feed per tooth at which the damage caused by brittle fracture is just above the final machined surface, r_d is the radial depth of cut, d is the vertical depth of fracture based damage, Y is the height of the point of brittle fracture point