Fracture-free Precision Machining of Sintered Tungsten Carbide by End-milling

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Abstract

Ductile-mode machining is an established technology to perform fracture-free machining of brittle materials. This paper presents the theoretical and experimental research results of ductile-mode machining of sintered tungsten carbide by endmilling. First, a theoretical cutting strategy is discussed based on the certain machining parameters. Peripheral milling tests were then performed on sintered tungsten carbide workpiece using PCD endmill to assess the validity of theoretical cutting strategy. Experimental results validated the theoretical strategy.

1 Introduction

Tungsten carbide renders poor machinability owing to its super hardness and high brittleness. Tungsten carbide products are typically fabricated by powder metallurgy process. Powder metallurgy process involves large capital investment and hence is not feasible for short run production or prototyping. It is therefore highly desired to develop conventional machining process as rapid means of producing tungsten carbide prototypes directly from the blank workpiece. The major challenge in machining a typically brittle material is to suppress the crack propagation so that chip formation becomes the predominant mechanism of material removal. Such machining approach is known as ductile-mode machining of brittle materials. It is believed that if the undeformed chip thickness is less than cutting edge radius and cutting edge radius is at microscale, tungsten carbide can be machined to achieve fracture-free surface. At such small scale of machining, the energy required to cause brittle fracture exceeds the energy required for plastic deformation and hence plastic deformation becomes the predominant mechanism of material removal [1]. Ductile-mode machining of brittle materials has been discussed in the past literature [1-2].

The objective of this study is to investigate the influence of some important machining parameters including cutting edge radius, feed per edge and radial depth of cut on ductile-brittle transition mechanism in microcutting of tungsten carbide by endmilling.

2 Theoretical Analysis

In milling process of brittle material with upmilling strategy, the undeformed chip thickness is the minimum at the beginning of the cut and then increases to the maximum value in the cut with rotation of the cutter. If the increasing undeformed chip thickness during the cut reaches the critical value at some point, brittle fracture takes place at that point. If the brittle fracture point is sufficiently high above the plane of final machined surface, the fractured zone will be removed by the subsequent cutting edge and final machined surface is crack-free as discussed in our previous study [3]. On the other hand if the brittle fracture occurs too close to the plane of final machined surface, fracture will extend into the final machined surface [3]. Hence, low feed per edge is considered propitious to achieve ductile-mode machined surface. Consider the schematic diagram in Fig. 1(a) where r_d is the radial depth of cut, $d = D/2-(D/2)\cos\theta_c$ is the subsurface damage depth, θ_c is the critical angle, f_{cr} is the critical feed per edge, D is the diameter of the cutter. Here, f_{cr} is defined as the maximum feed per edge at any given cutting condition to yield a crack-free machined surface. According to the theory of ductile-mode machining discussed above, if $r_d > d$, the critical feed per edge should remain constant. In this case, the subsequent edge should remove the fractured zone to produce a crack-free final machined surface. If $r_d < d$, the undeformed chip thickness must be prevented from reaching the critical value in the cut to produce a crack-free final machined surface as subsequent edge cannot remove the fractured zone completely and cracks will extend into the final machined surface. In case $r_d < d$, f_{cr} must be less than the limit i.e. $f_{cr} = t_c/\sin\theta_{max}$. Where $\theta_{max} = \cos^{-1}(D-2r_d)/D$ is the maximum tool-workpiece contact angle at a given radial depth of cut and t_c is critical undeformed chip thickness.

3 Experimental setup and procedure

The cutting experiments were performed on ultraprecision milling machine. PCD endmills of 5mm diameter but with three different edge radii were used. The edge

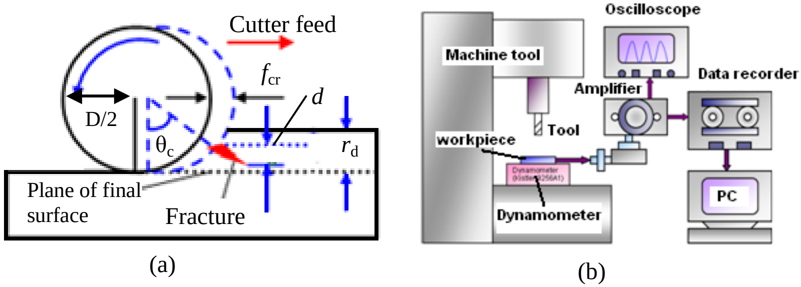


Figure 1: (a) Milling process of brittle material (b) Experimental setup

radii of the cutting tips were 2.9μm, 4.1μm and 5.2μm respectively. Sintered tungsten carbide workpieces of 0.5 mm in thickness were used and full thickness of the workpiece was cut by peripheral milling in upmilling direction. The experimental set is shown in Fig 1(b).

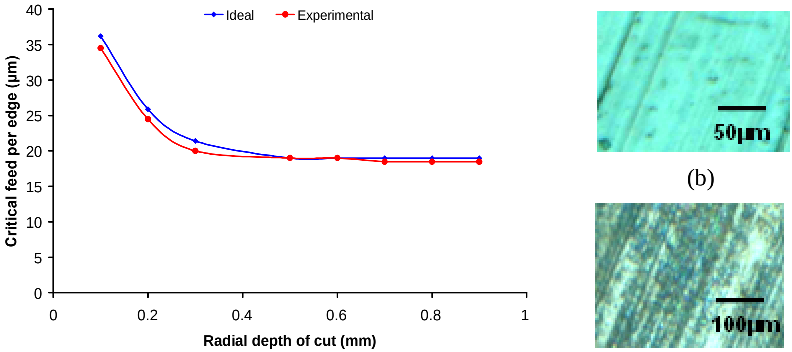
4 Results and discussion

4.1 Effect of edge radius on critical conditions

First set of experiments was performed to determine the critical chip thickness and critical feed per edge with cutters of different cutting edge radius. The method to determine the critical undeformed chip thickness has been discussed in detail in one of our previous study [3]. The experimentally achieved critical undeformed chip thickness value was found to be 1.8μm, 2.7μm and 3.0μm for cutters with cutting edge radius of 2.9μm, 4.1μm and 5.2μm respectively. The corresponding critical feed per edge value was found to be 16.5μm, 18.5μm and 19.0μm respectively. From this test, it has been identified that critical feed per edge and critical chip thickness increase with increase in cutting edge radius.

4.2 Effect of radial depth of cut on critical conditions

Second set of experiments was designed to determine f_{cr} by using cutters of 5mm diameter with cutting edge radius of 5.2μm. First, r_d was maintained greater than the empirically determined subsurface damage depth d. It can be seen that f_{cr} was noted to be reasonably constant for a range of values beyond a certain value of r_d. On the other hand in case of $r_d < d$, experimental f_{cr} was variable and is determined by the theoretical equation $f_{cr} = t_c/\sin\theta_{max}$ and it is significantly different from the constant value of f_{cr} achieved for $r_d > d$ case. The selective ductile and brittle mode machined surfaces are depicted in Fig 2(b, c). The empirically achieved values of f_{cr} for both the cases have been plotted in Fig 2(a) and this plot shows good fit to the theoretically predicted curve, therefore, validating the proposed theoretical analysis.



(a) (c)

Figure 2: (a) Effect of radial depth of cut on critical feed per edge (b) Typical ductile-mode machined surface (c) Typical brittle mode machined surface

5 Conclusions

It is concluded that the cutting edge radius, radial depth of cut and feed per edge influence the ductile-brittle transition in endmilling of brittle materials. However, feed per edge is the dominant factor. By varying the feed per edge, ductile-mode machining can be achieved by endmilling at a broad range of cutting conditions.

References:

[1] Fang, F.Z., Zhang, G.X. (2004). An experimental study of optical glass machining. Int. J. Adv. Manuf. Technol., 23(3-4): 155-160.

[2] Blacley W.S., Scattergood, R.O. (1991). Ductile-regime machining model for diamond turning of brittle materials. Prec. Eng., 13 (2): 95-103.

[3] Arif, M., Rahman, M., Wong Y.S. (2010). Analytical modeling of ductile-regime machining of tungsten carbide by endmilling, Int. J. Adv. Manuf. Technol (in press).