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Theoretical analysis and finite element simulation of Poisson burr in cutting ductile metals

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A B S T R A C T

In metal machining, due to the material around the cutting edge subjected to high pressure, the subsurface generates a plastic deformation layer. And near the edge of finished surface the plastic deformation layer acts as a Poisson burr. This paper proposes an analytical model to predict the sizes of Poisson burr based on Flamant and Boussinseq equations in the plastic deformation problem. Besides the mechanical loading, the thermal effects are also taken into account in this model and assumed as moving heat sources during the cutting. The finite element simulation of aluminum 6061 alloy is utilized to verify the results of theoretical analysis. The results show that the sizes of Poisson burr has a great sensitivity to material properties and processing parameters. In addition, due to the serrated chips and brittle fracture of high strain rate, the Poisson burrs are not continuous along the longitudinal cutting direction. Through comparative study it is found that the theoretical model describes burr sizes with considerable accuracy. As a result, this paper may provide a better understanding the mechanism of Poisson burr formation and the theoretical basis of processing parameters optimization.

1. Introduction

In most machining operations, an undesirable burr always generates near the edge of the part. Burr, together with chips, has been among the most troublesome obstructions to high productivity and automation of machining process [1]. According to the work of Gillespie [2] there are four types of burr based on the basic formation mechanisms, namely Poisson burr, rollover burr, tear burr and cut-off burr. No matter what kind of burrs, the existences of them have lots of disadvantages to the parts. On one hand, due to the real geometry of the workpiece edge is largely extent determined by the burr formation during the final manufacturing process, the burr causes the geometry size error of parts; On the other hand, burr which initially sticks to a part can be loose during the product operation and causes damage later on [3]. As a result, the deburring has to be applied in order to ensure the desired parts. However, deburring is time consuming and expensive. As pointed out by Gillespie [2], deburring and edge finishing on precision components may cost as much as 30 percent of the part cost [3]. Therefore, the best way of deburring is to study the mechanism of burr formation and the influences of processing parameters on the burr dimensions, as to minimize the burr sizes and move the burr into a less injurious location.

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Over the past decades, the formation mechanism and size predicition of burr have been carried out by using all kinds of research methods. Based on the work of Gillespie [2], Ko and Dornfeld [4] proposed a quantitative model of burr formation for ductile materials which did not include fracture during orthogonal machining. And the model including workpiece fracture during burr formation was further developed by Ko and Dornfeld [5] to predict the height and thickness of burr. In addition, the influence of oblique cutting on burr formation has also been researched by Ko and Dornfeld [6]. And the result of analysis showed that the burr size or fracture location decreases as the inclined angle of oblique cutting increases. Chern and Dornfeld [1] presented a model to analyze the mechanisms of burr formation and breakout in orthogonal cutting. They explained that bending and shearing are the dominant mechanisms for burr formation, while crack propagation along the negative deformation plane is the dominant mechanism for breakout. Toropov et al. [7] proposed a new model based on the theory of slip-lines and equilibrium equation to predict the full burr formation during orthogonal cutting. Except for the burr in orthogonal cutting, Toropov and Ko [8] studied the burr formation in the feed direction of turning. Their model provided reliable theoretical data regarding burr thickness, and can predict burr height with the maximum error of about 30%. In addition, the burr of milling operation is also greatly common and interested [9–11]. An analytical model for predicting the burr thickness in end milling of ductile material was proposed by Niknam and Songmene [9]. They found that an increase in feed rate and depth of cut leads to an increase in tangential cutting force and the thickness of burr. Niknam and Songmene [10] further developed the model to predict the thickness of burr, their new model studied the effects of a broad range of cutting parameters on cutting force, friction angle and burr thickness at the exit side of machined part, and found that smaller burr thickness is resulted with increased friction angle. Besides the milling operation, the burr of drilling operation has also been studied by many researchers [12–17]. Dornfeld *et al.* [13] studied the influence of an exit surface angle on drilling burr formation. And the optimization and control of drilling burr formation of AISI 304L and AISI 4118 based on drilling control charts were researched by Kim et al. [14]. However, it is an edge defect rather than a burr that generates during brittle materials cutting [18–20], Cao [18] studied the failure of exit edges in ceramic machining using finite element analysis, and the results revealed that the critical variables in determining the size of exit chipping are the crack site and length, loading orientation, and location. Zhou *et al.* [19,20] studied the formation mechanism of edge defects near the exit cutting SiCp/Al composites and the effects of cutting parameters on the sizes of edge defect. The results showed that the cutting velocity has little effect on the size of edge defect but the cutting depth has a significant effect on the height and length of edge defect.

The literatures regarding to the researches of burr mentioned above focus mainly on the rollover burr. However, as one of the most common burr in all kinds of machining operations, related researches about the morphology and sizes prediction of Poisson burr are hardly seen. In this paper, a theoretical model of Poisson burr is proposed to predict the thickness and height. The influences of material properties and processing parameters on the dimensions of Poisson burr are also analyzed detailedly. And the finite element simulation of aluminum 6061 alloy is used to investigate the morphology of Poisson burr and verify the predictive model. It is aimed to provide a fundamental understanding of the process variables and mechanics, necessary for processing parameters design.

2. The analytical model of Poisson burr

Metal machining is an extremely complex process which involves large plastic deformation, temperature rise and phase transformation in serve shear zone. As a result, the qualities of finished surface and subsurface play an important role in the part functionality [21]. Burr is one of the main characteristics on the finished surface and the results of surface plastic deformation. This paper develops a theoretical model of Poisson burr to predict the thickness and height, so as to reduce the dimensions of Poisson burr and the deburring energy.

2.1. The thickness of Poisson burr

The Poisson burr formation is mainly the result of plastic deformation on subsurface. In this paper, it is assumed that there is no phase transformation on the finished surface, namely the white layer is neglected. And the thickness of Poisson burr is equal to the depth of plastic deformation on subsurface. Therefore, to establish the analytical model of Poisson burr, the stress distribution of workpiece is analyzed in a physical approach focusing on cutting force and workpiece temperature. As the orthogonal cutting model shown in Fig. 1, the forces around the tool tips consist of cutting force and thrust force. And the components of cutting force [22] are expressed by Eq. (1).

$$\begin{cases} F_c = \frac{\tau wt \cos(\beta-\gamma)}{\sin\phi \cos(\phi+\beta-\gamma)} \\ F_f = \frac{\tau wt \sin(\beta-\gamma)}{\sin\phi \cos(\phi+\beta-\gamma)} \end{cases} \tag{1}$$

where F_c is the cutting force, F_f is thrust force, τ is the average shear stress, w the width of cut, t is the depth of cut, ϕ is the shear angle, β is the fiction angle, and γ is the rake angle. It is noted that the tool edge geometry is not taken consideration in the cutting forces expression. Therefore, the model is applicable when the uncut chip thickness is much larger than the edge radius. In addition, in order to calculate the burr sizes on cross-section, the average shear stress τ under the same processing parameters is assumed to be a constant during the cutting.