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Critical cutting speed for onset of serrated chip flow in high speed machining

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ABSTRACT

The transition of continuously smooth chip flow to periodically serrated chip flow as the cutting speed increasing is one of the most fundamental and challenging problems in high speed machining. Here, an explicit expression of the critical cutting speed for the onset of serrated chip flow, which is given in terms of material properties, uncut chip thickness and tool rake angle, is achieved based on dimensional analysis and numerical simulations. It could give reasonable predictions of the critical cutting speeds at which chips change from continuous to serrated for various metallic materials over wide ranges of uncut chip thickness and tool rake angle. More interestingly, it is found that, as the turbulent flow is controlled by the Reynolds number, the transition of the serrated chip flow mode is dominated by a Reynolds thermal number. Furthermore, the influences of material properties on the emergence of serrated chip flow are systematically investigated, the trends of which show good agreement with Recht's classical model.

1. Introduction

Cutting is a ubiquitous activity in daily life, science and technology [1,2]. The growing demand for enhancing production efficiency has stretched a rapid development of high speed machining (HSM) technology, which has many advantages such as high removal rates, low cutting forces, leading to excellent dimensional accuracy and surface finishing quality [3,4]. However, higher cutting speed usually renders the emergence of serrated chip flow [5], which ties up with decreased tool life, degradation of the surface finish and less accuracy in the machined part [6]. So, to predict the critical condition and especially the critical cutting speed for the onset of serrated chip flow could be of significant importance.

The mechanism for the onset of serrated chip flow has been extensively studied [7–12], and for most ductile metallic materials, the emergence of serrated chip flow is found be related to the thermoplastic shear instability occurred in the primary shear zone (PSZ) [8,9], which is often referred to the formation of adiabatic shear band [13–16]. And thus, considerable efforts have been carried out to focus on the adiabatic shear localization in the serrated chip formation process, and several classical theoretical models have been developed to predict the onset of serrated chip flow.

The first prediction for the emergence of serrated chip flow was provided by Recht [17]. He pointed out that when the tendency of the material in PSZ to harden with plastic deformation is overtaken by thermal softening effects, catastrophic shear occurs, and thus the serrated chip forms. A similar approach was proposed by von-Turkovich and Durham [18] to explain the transition of chip flow from continuous to serrated. It was assumed that such transition requires a maximum in the shear stress–shear strain curve. Hou and Komanduri [19] and Komanduri and Hou [20] extended Recht's classical model to predict the onset of shear instability. In their model, the possible sources of heat contributing toward the temperature rise are identified based on an analysis of the cyclic chip flow, and the temperature in the shear band was determined by using Jeager's classical methods. The shear stress in the shear band is calculated at the shear-band temperature and compared with the value of the shear strength of the bulk material at the preheating temperature. They stated that, once the shear stress in the shear band is less than or equal to the shear strength of the bulk material, shear localization is imminent.

The analytical model presented by Semiatin and Rao [21] is perhaps the first to provide a quantitative prediction of the critical speed at which the serrated chips are produced. Using the data available in the literature, the serrated flow is found to be imminent when the flow localization parameter (the ratio of the

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normalized flow softening rate to the strain rate sensitivity) is equal to or greater than 5. This model could give reasonable predictions of the critical speeds for the emergence of serrated chip flow in machining of AISI 4340 and 1045 steels, but the predicted critical speeds for titanium were much higher than the experimental findings reported by Recht [17]. Later, Xie et al. [22,23] extended Semiatin and Rao's model to investigate the effect of cutting conditions on the onset of shear localization in metal cutting. In their work, the power law relation was used to describe the material plastic behavior, and Loewen and Shaw's model was applied to estimate the shear band temperature. And thus the flow localization parameter can be expressed in terms of associated cutting conditions and properties of the work material. Once the flow localization parameter surpasses the critical value which should be determined experimentally, the shear localization occurs.

By applying ideas from the theory of the formation of adiabatic shear band in torsion, Molinari and Dudzinski [24] derived the condition under which continuous chip flow becomes unstable. Soon after, Burns and Davies [25,26] introduced the concept of a local deformation zone to treat the tool, chip and workpiece as a coupling system. They derived the critical condition for the onset of serrated chip flow by solving the differential equations for the force balance and heat balance inside PSZ. And they pointed out that the emergence of serrated chip flow can be explained as a supercritical Hopf bifurcation phenomenon: the limit cycle of the nonlinear dynamic system of tool–chip–workpiece.

With considering the effect of strain gradient which becomes important in the case of shear localization, Aifantis and his coworkers [27,28] presented a method for thermo-viscoplastic instability in chip formation to describe the serrated chip flow. In their work, the shear deformation inside PSZ is treated as a simple shear. They carried out the perturbation analysis to predict the onset of serrated chip flow, and the relations for the shear band width and spacing were also established. Similarly, also by using perturbation analysis, some other adiabatic shear critical conditions were built by Li et al. [29], Ye et al. [30] and Ma et al. [31]. In these works, some specific effects of HSM were considered. Li et al. [29] considered the compressive stress applied on the shear plane, and the adiabatic shear is found to be favored by larger compression stress; In Ye et al.'s work [30], the material convection coursed by the high speed chip flow was taken into consideration, and the material convection is proposed to be negative for the shear localization; Ma et al. [31] established a general criterion for predicting the material instability under combined stresses loading, and applied it to the orthogonal cutting process. They stated that, once the plastic work of shear deformation is larger than one-third of that of stretching deformation, or is larger than four times of that of shrinking deformation, the shear located instability is imminent, and the serrated chip flow emerges.

At recent, Childs [32] predicted the onset of serrated chip flow by introducing a thermal number. He pointed out that once the thermal number achieves a critical number, the shear localization occurs. However, the critical thermal number depends on the material properties and tool rake angle, which should be determined by experimentations or numerical simulations.

Besides the theoretical analysis, the finite element (FE) method has also been widely used to predict the onset of serrated chip flow. Bäker et al. [33] and Bäker [34] predicted the serrated chip formation when cutting Ti–6Al–4V alloy by using ABAQUS. The distance criterion for chip separation was used in their model, and the general trends concerning serrated chip flow were deduced related with the work material behavior. Rhim and Oh [35] proposed a new flow stress model which takes into account dynamic recrystallization to predict the adiabatic shear localization during cutting AISI 1045 steel. It was found that the serrated chips can be predicted by using the rigid plastic FE simulation together with the new flow stress model. Later, Arrazola et al. [36,37] modeled the 2D orthogonal cutting by using the Arbitrary Lagrangian Eulerian formulation proposed in ABAQUS/Explicit. The sensitivity of serrated chip prediction to the cutting speed and material input parameters was systematically analyzed. More recently, an adaptive numerical methodology was developed by Issa et al. [38] to predict the thermo-mechanical field localization in orthogonal cutting AISI 4340 stainless steel. In their work, the main thermo-mechanical phenomena such as the nonlinear isotropic and kinematic hardening with thermal and ductile damage effects were taken into account. And the effects of uncut chip thickness, initial temperature, friction coefficient and work ductility on the adiabatic shear localization were investigated. Using the Johnson–Cook damage criterion for chip separation and the modified Zorev model for tool–chip friction description, Duan and Zhang [39,40] developed a FE method to precisely predict the onset and the formation of serrated chip flow without artificial assumptions. And the effects of the cutting conditions were also investigated. Miguélez et al. [41] performed the FE simulations to predict the shear localization involved in high speed machining of Ti–6Al–4V in a wide range of cutting speeds and feed rates. The effects of some material parameters on shear flow stability were investigated. It states that, the strain hardening exponent has a stabilizing effect, and increasing the initial yield stress has a destabilizing effect on the onset of serrated chip flow.

It should be pointed out that, all these fantastic pioneer works give important clues for the understanding of the physics and mechanics of serrated chip flow. And for most of the theoretical instability criterions, they may give universal descriptions for the onset of serrated chip flow, since they were achieved based on the universal equations controlling the PSZ deformation. However, additional complex numerical calculations are usually required to predict the critical cutting speed at which the chip flow changes from continuous to serrated. As for the FE simulations, the onset of the serrated chip flow can be precisely predicted. However, it should be pointed out that, in cutting process the work materials differ widely in their ability to deform plastically, to fracture and to sustain tensile/compressive stresses [42], thus the onset of serrated chip flow could have strong dependence on the work material. But for most of the FE analyses, they are usually focusing on a certain work material. Moreover, though some fantastic pioneer FE analyses have qualitatively investigated the effects of material properties and cutting conditions on the onset of serrated chip flow, the quantitative relationship has not been established. And the universal explicit expression of the critical cutting speed for the onset of serrated chip flow is still unavailable.

In this work, high speed cuttings of various metallic materials were carried out over wide ranges of cutting speeds. Based on the experimental results, the dimensional analysis and numerical simulations were applied to predict the critical cutting speed at which the serrated chip flow is produced. The universal expression of the critical cutting speed for cutting metallic material by using sharp tools is given in terms of the material properties, uncut chip thickness and tool rake angle. It is demonstrated here that once the Reynolds thermal number achieves a critical value that dominated by the work material properties, the serrated chip flow emerges. This shows striking parallels to the turbulent flow which takes place as the Reynolds number surpasses a critical value determined by the fluid properties. Furthermore, the influences of the material properties on the onset of serrated chip flow are investigated systematically, the trends of which are in accordance with Recht's classical criterion.