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Finite element modeling and validation of chip segmentation in machining of AISI 1045 steel

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Abstract

The finite element (FE) method based modeling of chip formation in machining provides the ability to predict output parameters like cutting forces and chip geometry. One of the important characteristics of chip morphology is chip segmentation. Majority of the literature within chip segmentation show cutting speed (v_c) and feed rate (f) as the most influencing input parameters. The role of tool rake angle (α) on chip segmentation is limited and hence, the present study is aimed at understanding it. In addition, stress triaxiality's importance in damage model employed in FE method in capturing the influence of α on chip morphology transformation is also studied. Furthermore, microstructure characterization of chips was carried out using a scanning electron microscope (SEM) to understand the chip formation process for certain cutting conditions. The results show that the tool α influences chip segmentation phenomena and that the incorporation of a stress triaxiality factor in damage models is required to be able to predict the influence of the α. The variation of chip segmentation frequency with f is predicted qualitatively but the accuracy of prediction needs improvement.

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Keywords: damage modeling; stress triaxiality; chip segmentation

1. Introduction

Finite element (FE) based machining process models provide the ability to obtain the strain undergone by the workpiece material, the strain rate at which the workpiece material deformed and the heat generated in the primary and secondary deformation zones. With FE, cutting process parameters' influence on the chip morphology can be studied in detail.

Within chip morphology prediction, prediction of transition from continuous to segmented chip is of prime importance as they influence generated temperatures and cutting forces. In addition, segmented chip improves chip breakage and leads to better control of the cutting process. Therefore, chip segmentation modeling is expected to the continuous to segmented chip transition for cutting process parameter variation. Pioneering work in understanding chip segmentation in machining have carried about by Nakayama [1] and Komanduri et al. [2]. Nakayama [1] studied chip segmentation at lower cutting speeds for brittle materials and proposed periodic crack formation as the primary cause. These crack formations were initiated at the free surface edge of the shear plane. Komanduri et al.[2] studied the segmented chip formation at higher cutting speeds for ductile material and proposed the onset of a thermo-plastic instability which originates at the tool edge of the shear plane as the primary cause. Recent work by Wang and Liu [3] combined the theories mentioned above into "mixed mode of ductile fracture and adiabatic shear" theory to predict the continuous to segmented chip transition. They proposed the concept of critical cutting load defined as a multiplication of vc and f. The critical cutting load for AISI 1045 steel was in the range of 0.02 – 0.024 and 0.096 - 0.1 for 7050-T7451 Al alloy while keeping the rake angle (α) a constant of 0°. The chip segmentation boundary took

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the shape of negative power function with the x-axis defined by vc and y-axis defined by f.

Nomenclature

C_i	temperature coefficients
D	dimensionless cumulative damage
DOC	depth of cut
D_i	Autenrieth damage model coefficient
D_{JCi}	Johnson-Cook damage model coefficient
d_i	Advantedge damage model coefficient
f	feed rate
n	strain hardening coefficient
p	hydrostatic pressure
T	temperature
T_{cut}	cut off temperature
T_0	reference temperature
T_m	melting temperature
T_{tf}	transition temeperature for failure in Autenrieth's damage model
v_c	cutting speed
α	tool rake angle
σ_0	yield stress at reference temperature
σ	yield stress
σ_m	mean stress
$\bar{\sigma}$	equivalent stress
$\boldsymbol{\sigma}$	stress tensor
ε^f	strain at failure
$\dot{\varepsilon}_{eq}$	equivalent plastic strain rate
$\dot{\varepsilon}_0$	reference equivalent plastic strain rate
ε^p	plastic strain
$\dot{\varepsilon}$	plastic strain rate
$\dot{\varepsilon}_0^p$	reference plastic strain rate
ε_{cut}^p	cut off plastic strain
ε_i^p	instanteous strain increment
$\varepsilon_{f_i}^p$	instantaneous strain to failure
η	dimensionless hydrostatic pressure parameter

The theories as mentioned above show that chip segmentation is attributed to the shear band formation and is dependent on the workpiece material's response to thermo-mechanical loading in the cutting process. Duan and Wang [4] differentiated from a materials perspective the shear bands formed in machining into transformed shear bands and deformed shear bands. Transformed shear bands are formed in segmented chips during machining of workpiece materials such as hardened alloy steels, titanium alloys, and nickel-base alloys. The transformed shear band formations are attributed to adiabatic heating conditions [5] as proposed byt Komanduri et al [2]. At lower cutting speeds, deformed shear bands are produced in highly strain hardened workpiece materials and are influenced by f and α. This is explained by the crack propagation in the primary deformation zone as proposed by Nakayama [1].

To measure chip segmentation in machining, several parameters are available in literature with chip segmentation frequency being one of the most widely used. In addition, to study the segmented chip morphology, geometrical parameters like maximum chip thickness, minimum chip thickness, and chip segmentation length have been used. Atlati et al.[6] proposed the chip segmentation ratios using the above mentioned geometrical parameters as a global measure of shear strain. In addition, they also proposed the chip segmentation intensity ratio using the equivalent plastic strain inside and outside the shear bands. The equivalent plastic strains are obtained from FE simulations and are a local measure of the strain within the chip. Kouadri et al [7] used the chip segmentation ratios and chip segmentation intensity ratios to study the influence of two different rake angles with varying cutting speeds on chip segmentation in machining of AA202-T351 aluminum alloys. They showed that the v_c has a nonlinear proportionality to chip segmentation and is possible to control the chip morphology by identifying a combination of α and v_c. They also showed that smaller f (0.1 mm/rev) produced continuous chips and larger f (0.3 mm/rev) produced segmented chip for both conditions of α=0° and α=15°.

In FE, chip segmentation is modeled by modifying the material evolution laws. From the background of shear band formation theories described above, one can see that the modification of material evolution laws needs to be based on parameters such as stress triaxiality, Lode angle parameter, (to predict deformed shear bands) and temperature (to predict transformed shear bands). Adiabatic shear banding due to thermal instability leading to transformed shear bands is modeled by incorporating dynamic recrystallization phenomena (TANH model) [8], and modeling of strain at failure as a function of temperature, stress triaxiality, strain rate, lode angle parameter within a damage model could be used to model mixed mode of ductile fracture and adiabatic shear [6,9,10]

Johnson and Cook [10] developed a damage model used widely in metal cutting simulations for the prediction of chip segmentation that models failure at strain (ε^f) as follows

$$\varepsilon^f = \left[D_{JC1} + D_{JC2} e^{-D_{JC3}\eta}\right]\left[1 + D_{JC4} \ln \frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_0}\right]\left[1 + D_{JC5} \frac{T - T_0}{T_m - T_0}\right] \quad (1)$$

The equation incorporates stress triaxiality through the dimensionless hydrostatic pressure parameter η and is defined as follows

$$\eta = \frac{\sigma_m}{\bar{\sigma}} = \frac{-\left(\frac{1}{3}\right) tr(\sigma)}{\sqrt{\left(\frac{3}{2}\right)\sigma : \sigma}} \quad (2)$$

where σ_m is the first invariant of the stress tensor and $\bar{\sigma}$ is the third invariant of the stress tensor. The inclusion of the stress triaxiality within damage modeling in general was developed by Rice and Tracey [11] in the late 1970s to include the influence of hydrostatic stress on the fracture of ductile materials. The stress triaxiality parameter is used to define the influence of varying loading conditions on material failure. When a material is loaded in a mixed mode of compression, and shear as in machining, stress triaxiality becomes an important parameter to predict material failure accurately. Recent studies by Bai .[12] have shown that in addition to stress triaxiality, lode angle parameter is also an important influencing parameter for three-dimensional loading conditions.