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Modeling of microcrack formation in orthogonal machining

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ABSTRACT

Researchers have observed formation of microcracks during metal cutting and attributed their occurrence to various phenomena. Shaw postulated that under the combined shear and normal stress conditions on shear plane, microcracks could occur when strain in the shear plane exceeds the failure limit of material. However, the phenomenon of microcrack formation is difficult to capture experimentally. Therefore, this paper presents a finite element (FE) model to simulate the microcrack formation during orthogonal cutting. The model has been validated by performing orthogonal micro-cutting experiments and error in cutting force prediction is less than 11.5%. The simulation helps identify locations at which microcracks are formed in the shear zone using the mathematical and FEA models. Furthermore, the contribution of the specific energy (energy/volume) associated with the microcrack formation to the total specific energy of the shear zone has been evaluated. Contribution of microcracks to specific shear zone energy is found to be in the range of 0–20% for AISI 1215 and 0–15% for AISI 1045 under different machining conditions.

1. Introduction

Machining involves removal of work material normally with some kind of fracture. The fracture can be of varied dimensions and occurs at various locations in machining zones. Normally, gross and distributed type micro-fractures are observed in machining. In the past, these fractures have been studied and modeled by various researchers.

Gross fracture formation is known to occur even in ductile metals under certain cutting conditions and work material properties [1]. The cutting mechanism in ceramics was modeled by considering the propagation of small and sharp flaws (i.e., cracks) using the concept of fracture mechanics by Iwata and Ueda [2,3] and also analytically by Percy and Ueda [4]. Turkovich and Field [5] and Kluft et al. [6] showed that crack formation and its propagation during machining affect several aspects such as chip formation mechanism, cutting forces and machine surface integrity. Recently, analytical and numerical models for gross fracture formation in machining have been proposed by Atkins [7,8] and Subbiah and Melkote [1], respectively, in machining of ductile materials. Atkins [7,8] used fracture toughness to estimate the amount of energy consumed in material separation during the chip formation in machining. Subbiah and Melkote [1] presented an approach to model the metal cutting that captures ductile fracture leading to material separation using the FEA. Madhavan et al. [9] reported chip formation as an indentation process which is considered to be a result of occurrence of brittle/ductile fracture just ahead of the tool.

Other researchers have investigated the occurrence of microcracks or their accumulation leading to gross fracture along the shear zone during metal cutting. Komanduri and Brown [10] have experimentally shown the presence of microcracks in machining of low carbon steel and other ductile materials. The microcracks (or smaller voids) tend to disappear after unloading of the chip and hence, the size and the number of microcracks observed in the shear plane were not very accurate. Zhang and Bagchi [11] observed that micro-fracture during chip separation occurs by nucleation of voids in the vicinity of the tool tip. Iwata and Ueda [2] have observed mechanism of microcracks (flaws) growth to form a gross fracture in machining of ceramics. They have studied dynamic behavior of cracks in shear zone within the framework of fracture mechanics during machining. Luong [12] reported presence of microcracks during their experiments on specimen subjected to a loading similar to shear plane during metal cutting. But the quantification of density of microcracks was difficult on chip as reported by Komanduri and Brown [10]. In a pioneering work, Shaw [13] suggested that under the influence of unusually high shear stress and shear strain conditions in machining, localized fracture in the form of microcrack formation takes place

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Nomenclature

Symbol	Description
ALE	arbitrary Lagrangian–Eulerian
CDM	central difference method
CCD	charge coupled device
FEA	finite element analysis
OMM	on machine measurement
SPH	smoothed-particle hydrodynamics
A, B, C, n, and m	Johnson–Cook constant parameters for specified material
C_1 and C_2	material constants
C_d	damping co-efficient matrix
Fc	cutting force
E	Young's modulus of elasticity
IE_n	internal energy of nth time step
K	stiffness matrix
M	mass matrix
P	internal force
R^2	co-efficient of determination
T_{melt}	melting temperature of the material
T_{room}	room temperature of the material
V	cutting speed
$V_{element}$	element volume
f	feed
c	wave propagation speed
l	minimum element edge length
Δt	time step
$\Delta t_{critical}$	critical time step
u	displacement
$\dot{u}$	velocity
$\ddot{u}$	acceleration
$U_{sMicrocrack}$	specific microcrack energy
$U_{sShearZone}$	specific shear zone energy
$\varepsilon_{failure}$	failure strain in shear zone
ε^p	effective plastic strain value
$\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}$	non-dimensional plastic strain rate
η	triaxiality parameter
σ	normal stress on shear zone
σ_m	hydrostatic mean stress
$\overline{\sigma}$	equivalent stress
τ	shear stress of shear zone
γ	rake angle
ν	Poisson's ratio

along the shear plane. Discontinuous microcracks usually get initiated on the shear plane in the form of localized fracture (i.e., microcrack) during chip formation.

In general, microcracks have been used to explain several aspects of material behavior during machining such as, chip segmentation process [2], microcrack coalescence process in the vicinity of the tool tip [14], and the negative work hardening phenomenon observed due to microcracks in machining [15]. Shaw [16] also suggested that microcrack formation could contribute substantially to specific cutting energy (i.e., size effect) in metal cutting. Although, the gross fracture phenomenon ahead of the tool has been modeled to some extent, the formation of microcracks along shear zone during machining has not been modeled. This study focuses on understanding of the microcrack formation and its role in specific shear zone energy in metal cutting via numerical simulation. The study is based on the theory of microcrack formation in the deformation zone during the machining of ductile materials proposed by Shaw [13]. The theory postulated that shear stress and strain in metal cutting are unusually high and the discontinuous microcracks are usually formed on the shear plane. If the material being cut is brittle or compressive stresses on the shear plane are relatively low, microcracks grow into gross cracks thereby giving rise to discontinuous chip formation. However, the theory also suggests that the microcracks do get suppressed during the machining process and their number keeps varying in the process based on the cutting conditions. Moreover, literature reports [10,12,13], it is not possible to measure exact size and number of microcracks in shear zone during experiments on cutting due to their small size and unloading effect of quick-stop mechanism. In literature, there is no specific analytical or numerical formulation to estimate the number, the location and the contribution of the microcracks to specific shear zone energy during chip formation. Therefore, the objective of this study is to model microcrack formation in the shear zone during chip formation as postulated by Shaw [13] using framework of finite element analysis (FEA). The work presented in this paper uses the failure criteria suggested by Shaw to identify the location or the elements (in finite element model) undergoing failure. These locations correspond to the location of microcrack formation in shear zone. Thus, knowing the number of microcracks, their contribution in specific shear zone energy has been quantified as a function of processing parameters.

In the first section of this paper, the theory of microcrack formation in metal cutting is briefly explained followed by finite element analysis to identify and evaluate the number of failed elements referred to as microcracks during chip formation in the shear zone. The FEA model has been benchmarked with the experimental results. Finally, the contribution of microcracks to specific shear zone energy has been evaluated by comparing specific energy of the microcracks with the specific energy of shear zone in metal cutting.

2. Modeling of microcrack formation in machining

To model the microcrack formation in machining and to evaluate the contribution of microcracks in the specific energy of shear zone, the procedure shown in Fig. 1 has been used.

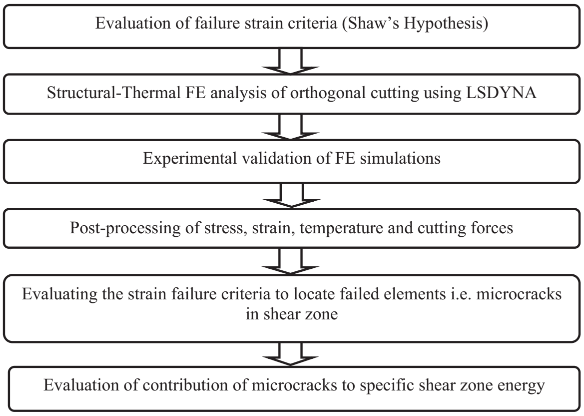

Fig. 1. Flow chart for modeling and contribution evaluation of microcracks in micro-cutting.