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An evaluation of different damage models when simulating the cutting process using FEM

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Abstract

The current study compares two damage modeling approaches in metal cutting finite element simulations; the Johnson-Cook shear failure model and the progressive damage model. The first assumes sudden failure when the set criterion is met; however, the second relies on two criteria; one for damage initiation and another for damage evolution. Simulations were performed on AISI 1045 steel, and different process parameters (forces, chip thickness, temperatures and plastic strain) were compared. Also, dry orthogonal cutting tests were performed and cutting forces and chip thickness were compared to the predicted values. The current results showed better predictions when damage evolution was considered.

Keywords: Machining; Damage; Finite element method (FEM).

1. Introduction

Finite element modelling (FEM) has been extensively used for simulating the metal cutting process, and predicting its different aspects. This includes, but not limited to, cryogenic machining [1,2], laser-assisted machining [3,4], surface integrity [5,6], effects of edge preparation [6,7], effects of workpiece material properties [8,9], and sequential cuts [1,10].

When Lagrangian FEM is used, a damage criterion is required for chip separation and segmentation. Furthermore, chip separation requires a parting line to be defined, along which material failure occurs generating the chip [9,11]. One of the most widely used damage models in metal cutting simulations is the Johnson-Cook (J-C) shear failure model [12], which is typically used in conjunction with the J-C constitutive equation [13]. The J-C failure model is based on the magnitude of equivalent plastic strain ($\bar{\varepsilon}^{pl}$) at the element integration points, where sudden failure is assumed when $\bar{\varepsilon}^{pl}$ reaches the set value for failure ($\bar{\varepsilon}_f^{pl}$); i.e., $\bar{\varepsilon}^{pl} = \bar{\varepsilon}_f^{pl}$ [12,14]. Examples of using the J-C failure model in metal cutting simulations could be found in [2,10,15,16].

Recently, over the past decade, researchers started to consider progressive damage in finite element (FE) simulations of metal cutting. This was in order to have smooth material degradation, and enhance computational stability [17-20]. To account for progressive damage, two criteria are required; a damage initiation criterion, and a damage evolution law that defines how failure progresses [14]. In the available literature, the J-C shear failure model was used as the initiation criterion, and damage evolution was based on fracture energy [17-20].

Abushawashi et al. [17] examined the effect of using damage evolution on the formation of serrated chips in FE simulations of cutting hardened AISI 1045. Orthogonal dry cutting tests were performed for model validation. The J-C constitutive equation was used to simulate material plasticity, and the J-C shear failure criterion was used for damage initiation. Damage evolution was based on the material fracture energy, where mode I and mode II were used for chip separation (parting line) and serration, respectively. Exponential damage evolution was assumed, and resulted in good agreement with the experimental results, in terms of chip morphology and cutting forces.

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Chen et al. [18] developed FE models and an analytical material flow stress model, which includes plastic flow and failure criterion, to determine the flow stress of Al7075-T6 during cutting. They used the J-C constitutive equation, and presented an improved form of the J-C shear failure model for damage initiation. The improved criterion took into account the effects of variation in strain rate, temperature and stress triaxiality, from one location to another, within the chip region. Damage evolution was modelled using the same approach of Abushawashi et al. [17]. The predicted results, including cutting forces and tool-chip contact length, were found to be in good agreement with experimental results.

Mabrouki et al. [19] simulated the process of dry orthogonal cutting of Al2024-T351 using FEM, with special focus on chip formation. Similar to the above works, they used the J-C failure model for damage initiation and fracture energy-based model for damage evolution. However, they used linear and exponential evolution rates in the parting line (mode I) and chip (mode II) regions, respectively. The predicted chip morphology was in good agreement with that obtained experimentally. Chen et al. [20] developed a modified form of the J-C failure model, with an energy-based ductile failure criterion, for Ti-6Al-4V. Again, the fracture energy density was used for damage evolution; however, linear evolution was assumed in both regions. The predicted forces and chip morphology were in good agreement with experimental measurements.

After a thorough review, it was found that researchers focused on examining the suitability of using damage evolution models for metal cutting FE simulations. However, they did not examine how this compares to the classical approach, where sudden failure is assumed after initiation. Also, none of them compared linear to exponential damage evolution. Therefore, the current work compares the use of two damage modelling approaches in FE metal cutting simulations. The first uses the J-C shear failure model in its classical form, as a sudden-damage prediction criterion; while, the second uses it as a damage initiation criterion accompanied by an energy-based damage evolution criterion. Plane strain FE analysis was used to model dry orthogonal cutting of AISI 1045, and cutting forces, chip thickness, workpiece temperatures and plastic strains were predicted. Also, orthogonal cutting tests were performed, where cutting forces and chip thickness were measured and compared to the predicted results.

Nomenclature

A, B, C	Johnson –Cook plasticity constants
D	Damage parameter
$\dot{D}$	Rate of change of damage parameter (D)
E	Young's modulus of intact material
E'	Young's modulus of degraded / damaged material
F_c	Cutting force component
F_t	Thrust force component
G_C	Critical fracture dissipation energy
G_f	Fracture energy dissipation
K_{IC}	Critical stress intensity factor (mode I)
L	Element characteristic length
T	Current temperature
T_r	Reference temperature
T_m	Melting temperature
d_1-d_5	Johnson-Cook failure parameters
lc	Tool-chip contact length
r	Chip compression ratio
t	Uncut chip thickness
$\bar{u}^{pl}$	Equivalent plastic displacement
$\dot{u}^{pl}$	Rate of change of equivalent plastic displacement
$\bar{\varepsilon}^{pl}$	Equivalent plastic strain
$\dot{\bar{\varepsilon}}^{pl}$	Equivalent plastic strain rate
$\dot{\varepsilon}_0$	Equivalent reference strain rate
$\Delta\bar{\varepsilon}^{pl}$	Equivalent plastic strain increment
φ	Shear angle
γ	Stress triaxiality ratio
α	Normal rake angle
$\bar{\sigma}$	Flow stress of intact material
σ'	Flow stress of degraded material
σ_y	Yield strength
ω	Scalar cumulative damage parameter
Suffix (unless listed above)	
f	Failure
0	State at the onset of damage
I, II	Mode-I and mode-II fractures, respectively

2. Damage modelling

2.1. Damage in ductile materials

When structural failure starts to occur, a material starts losing its load-carrying capacity and resistance to deformation. Accordingly, material damage is typically modelled in terms of stiffness degradation, and when the stiffness is totally lost the part is said to have completely failed. Fig. 1 [14] shows a typical uniaxial stress-strain curve of a ductile material. The curve starts with a linear elastic zone (*a-b*), followed by plastic yielding with strain hardening (*b-c*), and then the material starts losing its load-carrying capacity until complete fracture (*c-d*). In other words, point *c* represents the onset of damage; i.e., damage initiation, and point *d* represents complete damage. Region *b-c* is modelled using a flow stress model, the J-C constitutive equation (for example), and a damage initiation criterion, the J-C failure model (for example), is required for the onset of damage (definition of point *c*). Region *c-d*, which can be considered as the degraded response of *c-d'*, which the metal would have followed in case of no failure, is modelled using a damage evolution law [14,17-20]. At any point along the curve *c-d*, point *e* for example, the material is said to have a degraded Young's modulus *E'*, as given by Eq. 1. In Eq. 1, *E* represents Young's modulus of the intact material, and *D* is a damage parameter that ranges from 0 (case of no failure) to 1 (case of complete failure), as detailed below. At the same time, the flow stress of the degraded material (σ') is given by Eq. 2, where $\bar{\sigma}$ represents the flow stress of the material if failure did not occur (i.e., along the curve *c-d'*). It is important to note that, structural failure does not affect thermal properties; i.e., the thermal response of the material does not change in region *c-d* [14].