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Microstructure-based FEM simulation of metal cutting

Mustapha Abouridouane[a,]*, Fritz Klocke[a], Ayudita Oktafiani, Benjamin Döbbeler[a]

[a]*Laboratory for Machine Tools and Production Engineering (WZL),*
Chair of Manufacturing Technology, RWTH Aachen University, Steinbachstrasse 19, Aachen 52074, Germany

* Corresponding author. Tel.: +49-241-8028176; fax: +49-241-8022293. *E-mail address:* m.abouridouane@wzl.rwth-aachen.de.

Abstract

This paper presents a three-dimensional finite element approach to incorporate microstructure into micro cutting simulation based on the concept of a representative volume element (RVE) and constitutive material modeling as well as using the Lagrangian formulation proposed in the implicit FE code Deform 3D^{TM}. Finish broaching, micro milling and micro drilling tests using solid carbide tools with different cutting parameters are performed on ferrite-pearlite two-phase steel AISI 1045 for the verification of the developed 3D multiphase FE computation model regarding chip formation and cutting forces. The developed 3D multiphase FE model is successfully used to predict size effects in micro cutting.

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Keywords: Microstructure; Multiphase FEM; Micro Cutting; Size effects; RVE; Constitutive material law.

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1. Introduction

The mechanics of the cutting process on the microscopic level differ fundamentally from the conventional macro cutting. For example, the tool edge radius influences the cutting mechanism in micro machining significantly with regard to the effective rake angle, the minimum chip thickness, the dominance of ploughing and the related elasto-plastic deformation of the workpiece material [1-2]. These phenomena, known as size effects, have a profound impact on the cutting forces, process stability, and resulting surface finish in micro cutting.

Furthermore, the uncut chip thickness in micro cutting is on the same scale as the material’s grain size. Hence, the workpiece material cannot be assumed as homogeneous and isotropic. Especially, micro cutting of multiphase materials results in significantly varying cutting mechanisms and associated process response [3-6]. Microstructural effects in microscale cutting require quite different assumptions to be made concerning underlying material behaviour during micro cutting and have led to the need for new modeling approaches to account for such effects.

A popular tool in helping to explain the effects of microstructure during micro cutting is the use of finite element (FE) simulations. Due to the very complicated cutting process at the microscale and the higher modeling effort, most developed FE models for micro cutting heterogeneous materials are still limited at present to the two dimensional orthogonal cut and only give a qualitative prediction of simple plane strain cutting processes [7-10].

Based on the concept of a representative volume element (RVE) and constitutive material modeling, as well as the Lagrangian formulation proposed in the implicit FE code Deform 3D^{TM}, a 3D multiphase FE computational model is proposed in this paper to simulate explicitly micro cutting ferritic-pearlitic carbon steels. The paper has three parts. First, a material characterization including the analysis of the microstructure and constitutive equations for each phase ferrite, pearlite and composite ferritic-pearlitic carbon steel C45 (AISI 1045) is discussed. Then, the development of the multiphase 3D FE material model for steel C45 is described. Finally, the validation und the efficiency check of the developed multiphase FE model using micro drilling with and without built-in micro voids, micro milling and finish broaching are presented.

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2. Material characterisation

The material investigated in this research is the ferritic-pearlitic carbon steels C45. The material is hot drawn, shaved, ground, normalized and supplied as steel bar with a diameter of 10 mm. The microstructure of the work material is characterized with respect to the volume fractions of the two structural constituents, ferrite and pearlite and the grain size of ferrite, see Table 1.

Table 1. Microstructural data.

Steel	Carbon, w%	Pearlite, %	Ferrite, %	Ferrite grain size, µm
C45	0.45	60	40	15

The thermo-mechanical behaviour of the carbon steel used for the present work is described by means of the constitutive Johnson-Cook (JC) model. The JC model is a strain rate and temperature dependent visco-plastic material model [11], which describes the thermo-mechanical material flow behaviour (strain hardening, strain rate sensitivity, and thermal softening) over the entire strain rate and temperature range. The JC model uses the following equation for the equivalent flow stress:

$$\sigma = \left(A + B\varepsilon^{n}\right)\cdot\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\cdot\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^{m}\right] \qquad (1)$$

Where σ, ε, $\dot{\varepsilon}$ and T represent the equivalent flow stress, the equivalent plastic strain, the plastic strain rate and the absolute temperature, respectively. The JC parameters n (strain hardening exponent), C (strain rate sensitivity coefficient) and m (thermal softening exponent) describe the thermo-mechanical material behaviour. The remaining JC material parameters are A (the initial yield stress), B (the hardening modulus), (reference strain rate), T_r (reference temperature) and T_m (melting temperature). The JC equation parameters (A, B, n, C, m) are taken from earlier investigation [12] and listed in Table 2 for the steel C45 and its phases Ferrite and Pearlite. The reference parameters $\dot{\varepsilon}_0 = 0.002$ 1/s, $T_r = 20°C$, $T_m = 1500$ °C are specified.

Table 2. The parameter values of the JC equation for the carbon steels.

Steel	A, MPa	B, MPa	n, -	C, -	m, -
Pure ferrite	175	571	0.35	0.034	1.86
C45	546	487	0.25	0.015	1.22
Pure Pearlite	750	593	0.33	0.011	1.10

3. Microstructure-based 3D FE model for micro cutting

3.1. Heterogeneous 3D FE material model for steel C45

Based on the concept of RVE, a 3D two-phase FE material model was developed for the ferritic-pearlitic carbon steel C45. The RVE concept considers only a small material part that has the same average behaviour as a larger model. In the formulation of the FE material model, the microstructural data (phase volume fraction, ferrite grain size) and the constitutive description of the mechanical behaviour of each phase, determined above, were applied. Grain orientation, inclusions, micro defects and phase transformations were not considered in this approach due to simplicity and computational efficiency.

The major challenge of this approach was to generate a 3D RVE with a realistic morphology and sufficient number of grains, since the grain structures are 3D. In this context, some models like the Voronoi model [13] and micrograph model [14] have become established. The Voronoi algorithm utilizes a set of statistically distributed points (seeds) to partition space into region, i.e., Voronoi cells, one per point and hence to approximate a random microstructure. The Voronoi cells are created by considering each point and its nearest neighbours by application of a Delaunay triangulation algorithm. The micrograph model takes scanned pictures of the real material microstructure as input and creates a mesh. Basically, different phases are sorted out because of their color.

The approach used in this work is developed at the WZL and it is based on the Voronoi model. It starts with a predefined cubic (10^{-3} mm^3 or cylindrical: Ø 0.1 x 0.1 mm) FE mesh, as shown in Fig. 1. The grain generation occurs randomly in consideration of the ferrite grain size (average value: 15 µm) and the ferrite - pearlite volume fractions (40% - 60%). Compared to the above mentioned models, this approach is very reliable, computational attractive and the generation of the grain boundaries becomes very easy due to the predefined mesh. Fig. 1 shows the generated RVE for C45 with 300 grains and an average grain size of 15 µm. Compared to the real microstructure in cross and longitudinal section, the two-phase 3D FE model provides a realistic 3D microstructure, see Fig. 1.

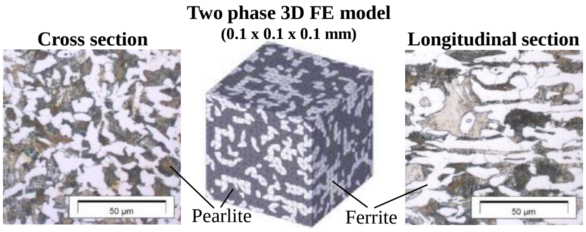

Fig. 1. Generated 3D RVE for the two-phase carbon steel C45.

To verify the developed 3D FE material model for C45, quasi-static compression, tension and shear tests were conducted on the investigated steel C45 at room temperature (compression specimen: Ø 4 x 4 mm, tension specimen: Ø 4 x 20 mm). The shear test was performed by means of a hat-shaped specimen with a web thickness (shear zone) of 0.1 mm [15]. The same tests were simulated using the developed RVE and FE code Deform 3D^{TM}. Fig. 2 shows a comparison between the experimental and computed flow curves under different loads. It is obvious that the developed multiphase 3D FE material model reproduces the mechanical behaviour of the real material C45 fairly well and can adequately be used for the simulation of micro cutting, provided that the RVE's volume is greater or equal to 10^{-3} mm^3.