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Advances in material and friction data for modelling of metal machining

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ABSTRACT

This paper reviews recent advances in constitutive and friction data and models for simulation of metal machining. Phenomenological and physically-based constitutive models commonly used in machining simulations are presented and discussed. Other topics include experimental techniques for acquiring data necessary to identify the constitutive model parameters, and recent advances in modelling of tool-workpiece friction and experimental techniques to acquire friction data under machining conditions. Additionally, thermo-physical properties for thermal modelling of the machining process, and microstructure data for the chip and workpiece together with relevant experimental methods are discussed. Future research needs in each of the focused areas are highlighted.

1. Introduction

Industrial machining processes are among the most complex manufacturing processes to model and simulate. In metal cutting, the complexities stem from the severe plastic deformation of the metal, and from the extreme tribological conditions present at the tool-workpiece interfaces [207]. The ability to accurately model and simulate cutting processes such as turning, milling, etc. depends on the availability of accurate mathematical models for (i) the constitutive response of the deforming material, i.e., a *constitutive model* that describes how the material yield strength and fracture behaviour change with deformation parameters such as strain, strain rate, temperature, microstructure, etc., and (ii) the friction at the tool and workpiece interfaces, i.e., *friction model*.

A major challenge in developing constitutive and friction models for metal cutting is the difficulty in acquiring dynamic stress–strain data and friction data, respectively, that accurately represent the cutting process. Historically, metal cutting modelling and simulation efforts have relied on stress-strain data derived from quasi-static and/or dynamic materials testing to calibrate constitutive models [107]. These data and associated constitutive models usually cover a limited range of strains, strain rates, and temperatures compared to those occurring in metal cutting. Consequently, the use of such constitutive models in machining simulations generally requires *extrapolation* to higher strains and strain rates, which contributes to inaccuracies in the simulated results. In the case of friction modelling, highly simplified friction models (e.g. Coulomb friction) are often used in machining simulations. The main reasons for this include limited knowledge of the complex frictional interactions at the tool-work interfaces, and a lack of suitable experimental techniques for measuring the relevant friction model parameters under conditions representative of metal cutting.

Other types of data critical for machining process modelling and simulation include temperature-dependent thermo-physical properties and workpiece microstructure data, which are often difficult to find or measure, for the materials and deformation conditions of interest. For instance, recent microstructure evolution dependent constitutive models for metal machining require microstructure data (e.g. grain size evolution as a function of strain, strain rate, and temperature) that are not readily available for many work materials of practical interest [144].

The objective of this keynote paper is to review and critically analyse recent advances and needs in material, friction, thermal, and microstructure data and associated models, along with experimental techniques for generating the data needed for accurately simulating the metal cutting process.

The paper is organized as follows. Section 2 discusses key aspects of constitutive data and models for metal cutting including phenomenological and physically based constitutive models,

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experimental techniques for generating the data required to fit the constitutive model parameters, methods for model parameter identification, a critical assessment of the data and models, and future research needs and opportunities. Section 3 reviews key aspects of friction in metal cutting, friction models and associated data requirements, and experimental methods for generating the friction data. Section 4 reviews thermal aspects of metal cutting, and the pertinent models and data. Section 5 reviews microstructure evolution in metal cutting, experimental methods for generating relevant microstructure data, and associated models. Section 6 concludes with a summary of the paper and a future outlook.

2. Constitutive data and models

2.1. Deformation characteristics in machining

2.1.1. Strains, strain rates, and temperatures

Metal machining is a severe plastic deformation process characterized by heterogeneous thermomechanical deformation of the metal at high deformation rates leading to the modification of the microstructure and material properties. Consequently, constitutive modelling for metal machining requires fundamental understanding of the deformation conditions in the relevant deformation zones (Fig. 1).

Accurate knowledge of the strains, strain rates, and temperatures are critical for understanding and controlling the machining process. Large strains (1–10), strain-rates (up to 10^6 s^{-1}) and temperatures (>1000 °C) are reported in metal cutting [10]. However, it should be noted that the large strains and strain-rates reported are often estimated using simplified shear plane based analytical models, which weren't validated using suitable experimental techniques capable of measuring such values under practical cutting conditions. Moreover, large temperatures are reported in the secondary deformation zone. In addition, the mechanical behaviour of the work material in machining also depends on other parameters such as the microstructure (e.g., dislocation density, grain size, etc.) [144] and the state-of-stress [27]. Therefore, proper identification of the deformation conditions and their ranges in metal cutting is essential for the design and selection of suitable mechanical tests to characterize the work material behaviour under conditions representative of metal cutting.

In-situ experimental techniques such as Particle Imaging Velocimetry (PIV) have been used to characterize the strain and strain-rate distributions in metal cutting [139]. In this technique, heterogeneous surface markers in the workpiece surface are tracked using high-speed imaging (Fig. 3). The strain fields are calculated using the relative displacements of the heterogeneous surface markers.

Using PIV, Brown et al. [37] estimated a strain-rate of ~20 s^{-1} in the primary shear zone and a shear strain of 2.05 in a OFHC copper chip at a very low cutting speed of 0.3 m/min. In order to estimate the strain and strain-rate, they used a classical shear plane based analytical model. Huang et al. [113] performed similar experiments on Ti–6Al–4V at a comparable low cutting speed of 0.6 m/min and they estimated strain-rates of ~40–80 s^{-1} and a strain of ~1.5.

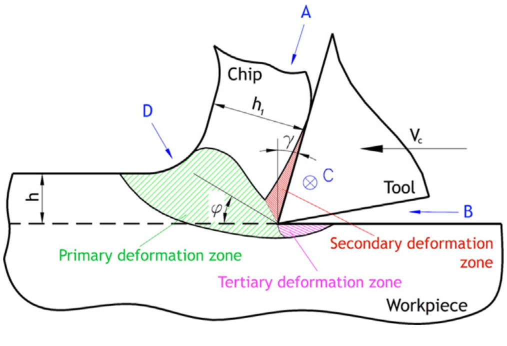

Fig. 1. Deformation zones in the metal cutting process.

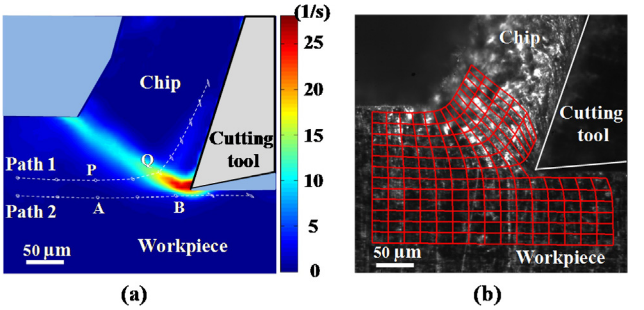

Fig. 2. PIV technique used to characterize deformation in machining: (a) Effective strain rate field, (b) Grid distortion [102].

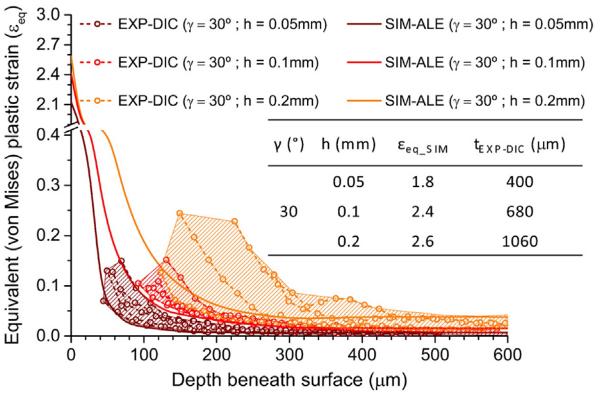

Fig. 3. Measured and predicted through-depth plastic strain distributions at different uncut chip thicknesses [167].

In general, the PIV technique is restricted to measurements at low cutting speeds due to imaging speed limitations. Nevertheless, it is a very useful in-situ technique to understand and quantify the deformation field in metal cutting.

Recently, Sagapuram [194] used high speed imaging to investigate the mechanism of shear-localized chip formation in orthogonal cutting of Ti–6Al–4V at cutting speeds of 0.25 m/s–5 m/s. Using a combination of marker displacement techniques and microscopy, they estimated the average shear strain in the shear band to range from ~10 (at 0.25 m/s) to ~40 (at 5 m/s). Shear strain rate in the shear band region was estimated to be ~4 × 10^5 s^{-1} at a cutting speed of 1 m/s.

Outeiro et al. [167] used the Digital Image Correlation (DIC) technique to estimate subsurface plastic strains produced in orthogonal cutting of OFHC copper at a cutting speed of 90 m/min. They estimated the maximum von Mises equivalent strain to be ~0.25 at 150 μm below the cut surface for an undeformed chip thickness (h) of 0.2 mm (Fig. 2). The authors note that further improvements in DIC are required to determine the maximum strains, which occur near the machined surface.

Accurate measurements of the cutting temperatures in the primary deformation zone, and in the secondary deformation zone, primarily due to tool-chip friction, are important for understanding their impact on the flow stress of the work material during cutting, and on the tool wear as well. High temperatures normally observed at the tool-chip interface accelerate tool wear, which can degrade the machined part surface integrity. However, the high temperatures in the secondary deformation zone normally do not affect work material behaviour in the primary deformation zone. As noted by Astakhov [11], under practical cutting conditions (Péclet number, Pe >> 10), the heat generated in the primary and secondary deformation zones is transported away from the zones by the fast moving chip because the chip velocity is much greater than the rate of heat conduction.

The challenge is to measure the temperatures in the primary deformation zone accurately and at a sufficiently high resolution.

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