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Inverse method for estimating shear stress in machining

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ABSTRACT

An inverse method is presented for estimating shear stress in the work material in the region of chip–tool contact along the rake face of the tool during orthogonal machining. The method is motivated by a model of heat generation in the chip, which is based on a two-zone contact model for friction along the rake face, and an estimate of the steady-state flow of heat into the cutting tool. Given an experimentally determined discrete set of steady-state temperature measurements along the rake face of the tool, it is shown how to estimate the corresponding shear stress distribution on the rake face, even when no friction model is specified.

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1. Introduction

After more than three-quarters of a century of research in the mechanics of machining processes, a period starting in the early 1890s with the tool-life studies of Taylor (1907) (see, e.g., Kalpakjian and Schmid, 2009), which Usui and Shirakashi (1982) refer to as "descriptive," the introduction of software based on finite element analysis (FEA) methods, beginning in the 1970s (Zienkiewicz, 1971; Kakino, 1971; Shirakashi and Usui, 1976) encouraged the hope that a "predictive" machining theory could be developed, so that important process variables such as spindle speeds, cutting forces, chip thicknesses, and especially peak tool temperatures, could be estimated accurately, and machining operations could be optimized, without requiring expensive trial and error experimentation. However, after almost another half-century of research, and despite the many advances that modern finite-element analysis software packages incorporate, it has become apparent that these models need adjustment and tuning for a given application, and truly predictive software is not yet available.

A major reason for the lack of predictive capability of finite-element based machining models is the lack of good constitutive response models for work materials. It is difficult to estimate the flow stress under extreme conditions of rapid, very large, and localized shearing deformation, heating rates as high as one million degrees Celsius per second, resulting in enormous temperature gradients, and peak temperatures on the order of 1000 °C, in the thin primary shear zone where cutting takes place, and in the secondary shear zone, a thin boundary layer in which the work material continues to deform as it moves along the cutting edge of the tool; see Fig. 1. The thickness of this layer decreases with increasing cutting speed (see, e.g., Trent and Wright, 2000), which makes estimates of local variables such as strain extremely difficult to obtain

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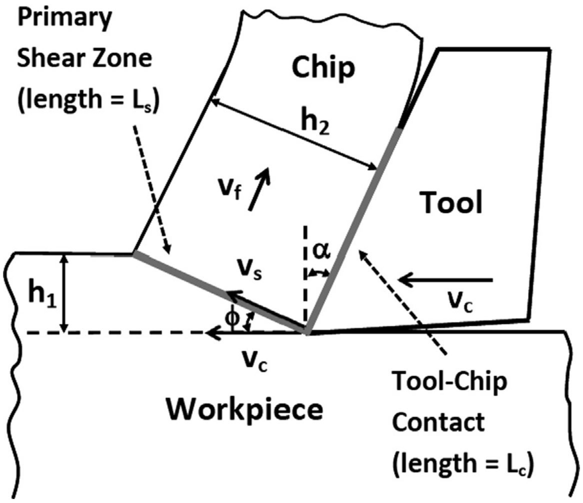

Fig. 1. Idealized model of chip flow in orthogonal cutting.

experimentally.

In what follows, we will first review some NIST work on the medium carbon steel AISI 1045. AISI 1045 is widely used in automotive and heavy equipment manufacturing for component parts, such as crankshafts, gears, axles, and connecting rods, because of its machinability, strength properties, and resistance to wear. These are among the reasons that it was the material chosen for the "Assessment of Machining Models" (AMM) study (Ivester et al., 2000), that was performed jointly by the National Institute of Standards and Technology (NIST) and the International Academy for Production Engineering – College International pour la Recherche en Productique (CIRP).

In work performed at NIST that was related to the AMM, new non-contact thermometric techniques were developed, to image one of the side faces of the tool and of the workpiece, in order to obtain an estimate of the 1D temperature distribution on the tool–chip interface during plane strain, steady-state orthogonal machining tests on AISI 1045 (Davies et al., 2003b). As follow-ons to this study, computer simulations were performed, in an attempt to model the temperature field in the chip. It was found that finite-element simulations, using the commercial software package Abaqus (2003), with a Coulomb sliding friction model to simulate the tool–chip interaction on the rake face, and three different constitutive models for AISI 1045, two of which had been specifically developed for machining simulations, underpredicted the measured peak tool–chip interface temperatures by as much as 300 °C (Davies et al., 2003a). These results, which support the hypothesis that there is too much thermal softening in the constitutive response models for AISI 1045, will be reviewed briefly in Section 2.

Another project related to the AMM work has been the development of the NIST Pulse-Heated Kolsky Bar Laboratory (Mates et al., 2008, 2009). This laboratory combines a split-Hopkinson pressure bar (Rhorer et al., 2002) with a rapid heating and thermal measurement system (Basak et al., 2003, 2004; Yoon et al., 2003; Whitenton, 2005), so that a test sample can be pre-heated in situ to a specified temperature in a few seconds, prior to loading the sample in compression. Using this laboratory, we have demonstrated that AISI 1045 steel has a significantly stiffer constitutive response when it is rapidly pre-heated, than when it is pre-heated more slowly, on a time scale on the order of minutes (Burns et al., 2012). We will also show in Section 2, that when this stiffer constitutive response is incorporated into a Johnson–Cook constitutive model and used in Abaqus, with the same Coulomb friction model, to simulate the temperature in the chip during orthogonal cutting of AISI 1045, it gives improved peak rake face temperature predictions, but the results still underpredict the temperature by as much as 150 °C.

One area of machining research in which significant progress has been made in the past few years has been the measurement of the 2D temperature distribution on the chip–tool interface, using infrared thermography. In particular, Menon and Madhavan (2014) have reported high accuracy temperature measurements in Ti–6Al–4V, using single wavelength thermography with an instrumented, transparent yttrium aluminium garnet (YAG) tool. For their experimental cutting conditions, which produced shear-localized chips, and measured peak temperatures of 900–1000 °C, they have obtained a 1D temperature distribution as a function of distance along the rake face of the tool, along an internal cross section of the chip–tool interface, with an estimated uncertainty in the temperature of less than 6 °C. Motivated by this work, the main purpose of the present paper is to investigate and to provide an affirmative answer to the following theoretical question. Assume that it is possible to obtain good in situ temperature measurements along an internal 1D cross section of the chip–tool interface during a steady-state orthogonal machining operation that produces continuous chips. Can these data be used to obtain an estimate of the associated 1D shear stress distribution in the chip near the rake face?

Our approach to addressing this question builds on early theoretical modeling of the chip temperature that was done by Rapier (1954) and Weiner (1955). Rapier assumed that the chip material leaves the primary shear zone, treated as a surface