Mechanics of Materials 77 (2014) 43–51

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Identification of plasticity constants from orthogonal cutting and inverse analysis

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ARTICLE INFO

Article history:
Received 16 April 2014
Received in revised form 11 June 2014
Available online 11 July 2014

Keywords:
Orthogonal cutting
Johnson Cook
Inverse analysis
Kalman filter

ABSTRACT

The aim of this work is that from experimental determined cutting process parameters be able to predict the plasticity input constants to Finite Element Method (FEM) models. In the present study the Johnson–Cook constitutive model constants are determined on the basis of cutting process parameters in orthogonal cutting and by use of inverse analysis. Previously established links between Johnson–Cook constitutive model constants and cutting process parameters in the cutting process such as primary cutting force and chip compression ratio is used serve as a starting point in the inverse analysis. As a reference material AISI 4140 has been chosen in this study, which is a tempered steel. The Johnson–Cook constitutive model constants in the reference material are being changed within an interval of ±30%. The inverse analysis is performed using a Kalman filter. The material model for the reference material is validated on the basis of the experimental results in previous work. The model showed to predict the cutting process parameters with a high level of accuracy. The predicted Johnson–Cook constitutive model constants in the present study achieve an error between simulated- and experimental cutting process parameters of maximum 2%. The method described in this study is not limited to identify Johnson–Cook constitutive model constants, but the method can also be used for other constitutive models. The same applies to the process itself and the selected cutting process parameters, but orthogonal cutting has been used to illustrate and validate this method.

1. Introduction

The reliability of numerical models such as FEM depends on various mechanical properties such as elastic constants, flow stress and fracture, these serve as material constants in constitutive models. In addition for a coupled thermo-mechanical simulation thermo-physical constants, such as thermal conductivity, heat capacity and plastic deformation energy also comes into account. For a simulation where contact between bodies is present, the contact conditions at interfaces both mechanical and thermal also need to be defined. All three of these aspects have to be taken into account when simulating a machining process. The Johnson–Cook plasticity model is widely used today to simulate materials subjected to high a temperature and strain rate gradients which are the case in a machining process. The Johnson–Cook plasticity model has been successfully used by many researchers to simulate various aspects of the machining process such as temperature distribution in the workpiece (Chen et al., 2004; Özel and Zeren, 2007), cutting forces (Hortig and Svendsen, 2007; Uhlmann et al., 2007), residual stresses in the machined surface (Mabrouki et al., 2008; Umbrello et al., 2007), strain in the deformation zones (Pujana et al., 2007; Zouhar and Piska, 2008) and chip formation characteristics (Akbar et al., 2010;Zhang et al., 2011). FEM simulation of manufacturing processes has been found to be a cost

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http://dx.doi.org/10.1016/j.mechmat.2014.07.005

effective method of analyzing such processes, serving to keep the amount of experimental work and the resources needed at a minimum. This is in the line with use of a sustainable production approach.

A drawback when using FEM to simulate a cutting process however, is the lack of input data to the material models involved. There is thus a need of establishing a robust link between experimental data and the material constants of the constitutive models. Achieving this would considerably reduce the efforts needed to find input constants to FEM models. The development of these plasticity constants for the cutting process has been studied from different viewpoints. First, through the use and adjustment of laboratory testing experiments for the construction of material constitutive laws in conditions similar to those encountered in machining operations, such as Split-Hopkinson's (Chandrasekaran and M'saoubi, 2005; Jaspers and Dautzenberg, 2002), second by the use of analytical cutting models (Tounsi et al., 2002) or numerical (Fallböhmer and Altan, 1997) in a combination with an inverse analysis.

Due to the severe deformation conditions present in the cutting process, it is possible to reach strains of the order of magnitude 1–2, strain rates higher than $10^4\,\mathrm{s}^{-1}$, temperatures up to 1000 °C and temperature rates up to the order of $10^6\,{}^\circ\mathrm{C\,s}^{-1}$ (Arsecularatne and Zhang, 2004). These experimental tests methods, such as Split-Hopkinson's, however are not able to produce as high strain rates or temperature rates that are present in the machining process deformation zones. Therefore it is desired to tune the constants in the constitutive models with experimental data from the actual cutting process.

How the Johnson–Cook constitutive model constants affect the cutting process parameters of the cutting process, such as chip compression ratio, cutting forces, temperatures and deformation zones was investigated in (Agmell et al., 2013). For simulation of the cutting process, even in a simplified orthogonal case, one can identify about 30 different cutting process parameters of interest related to tool development and analysis of the machinability of the workpiece material. The material that has been simulated is AISI 4140 where the FEM model used in (Agmell et al., 2011) has been employed and Johnson–Cook constitutive model constants being changed within the interval of ±30%. The present study was carried out to obtain a better understanding of how the Johnson–Cook constitutive model constants should vary within a material group according to the ISO standard having cutting process parameters that are similar. In the work reported on here, the variation of the cutting process parameters is studied for each of the Johnson–Cook constitutive model constants respectively, when they are changed by ±15% and ±30% for each constant. A polynomial function of the fourth order is interpolated between these data points. An inverse analysis using a Kalman filter is performed in order to determine the Johnson–Cook constitutive model constants. The Kalman filter has been successfully used for inverse identification of mechanical properties in Aoki et al. (1997), Bocciarelli et al. (2005), Delalleau et al. (2006), Nakamura and Gu (2007) which suggest that it can be a feasible method. To validate the method and the estimated Johnson–Cook constitutive model constants, new FEM simulations of the cutting process was carried out; the cutting process parameters obtained are then compared with experimental values from the experiments performed.

2. Machining mechanics and theoretical aspects

The parameters that will be presented in this section are general cutting parameters used to describe an orthogonal cutting process. The uncut chip thickness h_1 is defined as the uncut thickness of the chip or the distance between the surface prior to machining and the newly formed surface. The cutting speed v_c of a machining operation is defined as the relative speed of the workpiece to the cutting edge. The friction at interface between the tool and the workpiece decelerates the chip, which causes the chip thickness h_2 to be larger than the uncut chip thickness h_1. The chip velocity, v_{ch} will as a result, be lower than the cutting speed. If the workpiece is considered to be incompressible, mass balance requires that h_2 is larger than h_1 and the chip compression ratio exceeds unity, defined as $\lambda_h = h_2/h_1$, (Ståhl, 2012). See Fig. 1 for an illustration. The tool geometry parameters that are present in this article are as follows. The edge radius r_β is the radius of the edge on the cutting tool, the rake angle, γ is the angle between a plane perpendicular to the idealized new surface and the rake face of the tool. The clearance angle, α is the angle between a plane parallel with the idealized new surface and the clearance face of the tool. An illustration of the three tool parameters described can be seen in Fig. 2. The resultant force in a turning process can be decomposed into the three orthogonal components. The component acting in the cutting speed direction is referred to as the primary cutting force F_c. This is usually the largest of the three components. The component acting in the axial feed direction is referred as the feed force F_f. This is often the second largest force component. The third component acts in the radial feed direction is the smallest of the force components and it is called the passive force F_p. In the two dimensional case or orthogonal cutting case, the only active forces are the primary cutting force F_c and the feed force F_f as seen in Fig. 3.

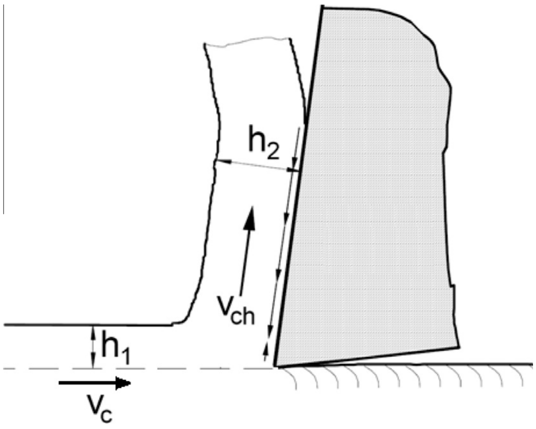

Fig. 1. The two dimensional approximation of an orthogonal cutting process.