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Technical Paper

Heat matters when matter heats – The effect of temperature-dependent material properties on metal cutting simulations

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ABSTRACT

The goal of metal cutting research is to predict process conditions accurately with a model or a simulation, in order to optimize and develop the processes. Development of such a model requires understanding of multiple branches of physics and engineering such as continuum mechanics, thermodynamics, tribology and materials science. For an accurate model, each aspect of the process must be modelled properly, or at least the effects of a certain phenomenon must be shown to be negligible. This paper investigates the effect of the temperature dependence of material properties on metal cutting simulations for three different engineering materials: AISI 1045 steel, AISI 7075 aluminium and AISI 304 stainless steel. It is generally accepted that the flow stress of metals is dependent on the temperature, but modulus of elasticity, thermal expansion, heat capacity and thermal conductivity are often considered constants and their effect is considered negligible. In this study, orthogonal turning of the materials is simulated with constant material properties and material properties that are functions of temperature. Each material property combination is simulated to test their effect on the results to investigate the individual and interdependent effects. Based on the results, a general guideline can be formed regarding the importance of heat capacity, thermal conductivity, modulus of elasticity and heat transfer.

1. Introduction

Metal cutting is a highly temperature-dependent process. Flow stress, damage and friction are each functions of temperature and thus temperature affects tool wear, cutting forces, chip thickness and surface finish both directly and indirectly. Finite element simulations have been used for some time now in metal cutting research as a tool to dive more deeply into the deformation problem than it is possible with mere cutting experiments. Early works published before 2002 in cutting simulations are listed in bibliographies by Jaroslav Mackerle [1,2]. The first commercial FEM codes for metal cutting are Third Wave Systems AdvantEdge and Scientific Forming Technologies Corporation Deform. The method behind AdvantEdge is presented in Marusich and Ortiz [3]. First publications about the development of Deform are about metal forming and written by Kobayashi and Altan [4,5]. Author's previous work investigated the aforementioned commercial solvers, their applicability, later material modelling, and model parameter acquisition. The simulations were found to be relatively accurate in comparison to experiments, and largest error source was identified to be material model [6,7]. The goal of this paper is to investigate the effects of temperature-dependent material properties on simulation accuracy, since the effects of temperature-dependent properties are often overlooked and considered constants instead of functions of temperature. One indication of such a perspective is the limited number of papers published on temperature-dependent material properties. To address this issue, orthogonal cutting of three different engineering materials, AISI 7075 aluminium, AISI 1045 steel and AISI 304 stainless steel, are simulated with respect to their temperature-dependent material properties. The simulation results are also compared to experimental results to verify the models. The properties that are considered in this paper, in addition to the flow stress, are the modulus of elasticity, thermal expansion, heat capacity and thermal conductivity.

Only a few previous papers have previously discussed temperature-dependent material properties and modelled them as functions of temperature. Weifen et al. presented a FEM model of cutting with temperature-dependent material parameters [8]. The paper investigates the effect of cutting parameters on the simulation output, but the effect of the temperature dependence of material properties was not considered in the results. Ding and Shin presented a thorough simulation model of AISI 1045 steel with a coupled thermomechanical and metallurgical analysis [9]. The key finding in the paper was that simulation accuracy increases with a coupled metallo-thermomechanical model compared to traditional models. Grzesik and Nieslony investigated the tool-chip interface of different tool coatings via several experiments and applied an

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analytical method while machining AISI 1045, AISI 304 and ARMCO [10]. The findings presented in the paper are related to the technological implications of the tool coatings. In Nieslony et al. thermal softening sensitivity of flow stress model was investigated regarding softening parameters and which stress-strain-temperature data is used [11]. The results show that the thermal softening function has significant effect on the results of cutting simulations. The effect of thermal softening in Johnson-Cook model can be observed in Agmell et al., where inverse analysis of J-C parameters was done to calibrate the model to fit AISI 4140. The model parameter *m*, i.e. the thermal softening exponent, has largest individual effect out of the J-C parameters regarding cutting force, strain in workpiece, chip compression ratio and cutting temperature [12]. However, none of the papers discussed the effect of the temperature dependency of thermal properties on the accuracy of the simulations. Similar to the idea of this paper, an investigation of the effects of the Johnson-Cook model parameters of different engineering materials on the simulation results was conducted by Umbrello et al. in 2007. The paper applied temperature-dependent density, specific heat and thermal conductivity, but again, the effect of the thermal parameters was not investigated [13]. Putz et al. did comprehensive analysis on orthogonal cutting of Inconel 718 [14]. Their material was modelled with Johnson-Cook model and Cockroft-Latham damage model and included temperature dependent specific heat and thermal conductivity to investigate the heat flux generated in cutting. The model was in good agreement with experiments regarding chip temperature, but feed force was underestimated. The role of the temperature dependence of the specific heat or thermal conductivity was not discussed. Arrazola et al. have done wide review on recent developments in metal cutting modelling [15]. They cover number of papers discussing thermal properties and their effect on metal cutting, but the focus was on heat flux and the individual material properties were not discussed in detail. Zemzemi et al. devised a new method to measure sliding velocity dependent friction and heat flux in machining and found that heat flux from workpiece to the tool increases with sliding velocity [16]. Yen et al. simulated cutting tool friction found that tool temperature is highly sensitive to the tool-chip interface heat transfer coefficient [17]. There are multiple other papers discussing the role of heat flux or heat transfer in machining like [18,19], but none of them investigate the role of temperature dependence of heat capacity, thermal conductivity, thermal expansion or elasticity, and moreover, the parameters are considered constants more often than not. This paper aims to answer the question: Is it justified to consider heat capacity, thermal conductivity, modulus of elasticity and heat transfer as constants instead of functions of temperature?

Table 1
Cutting parameters for the simulations and experiments.

	v_c (m/min)	f (mm/r)	a (mm)	α (°)	γ (°)
AISI 1045	300	0.3	1.6	5	5
AISI 7075	237.6	0.2	3.81	5	5
AISI 304	140	0.4	4	−7	7

2. Materials and methods

The finite element software used in this study is Deform from the Scientific Forming Technologies Corporation, which uses a Lagrangian formulation and a quasi-static, implicit time integration scheme. The simulations were done in 2D turning for AISI 1045 and AISI 7075, while AISI 304 was simulated in both 2D and 3D. The simulations were done with an elastic-plastic material model with strain, strain rate and temperature-dependent flow stress using the Johnson-Cook flow stress model (Eq. (1)) for AISI 1045, AISI 7075 and AISI 304 [20].

$$\sigma = \left(A + B\varepsilon^{n}\right)\left[1 + C\ln\left({}^{\dot{\varepsilon}}/_{\varepsilon_{ref}}\right)\right]\left[1 - \left({}^{T - T_{ref}}/_{T_{melt} - T_{ref}}\right)^{m}\right] \quad (1)$$

Where A = Yield Equivalent, B = Strain Hardening Multiplier, C = Rate Hardening Multiplier, n = Strain Hardening Exponent, m = Thermal Softening Exponent, ε = Strain, $\dot{\varepsilon}$ = Strain Rate T = Temperature, T_{ref} = Reference Temperature, T_{melt} = Melting Temperature.

AISI 304 was simulated with Cockroft-Latham damage model [21], that calculates the maximum principal stress integrated over the deformation in each element, and when that value reaches predetermined critical value, those elements are either deleted or the flow stress is decreased a certain percentage. The model is given in Eq. (2).

$$C_{crit} = \int^{\varepsilon} \sigma * d\varepsilon \quad (2)$$

Where σ^* = maximum principal stress and C_{crit} = critical value

The tool was modelled as rigid, and tool wear was not considered. The tool was a generic carbide tool for the 2D simulations of AISI 1045 and AISI 7075 and a *TiN* coated Sandvik Coromant DNMG150608 insert for the AISI 304 simulations. The cutting parameter values are presented in Table 1.

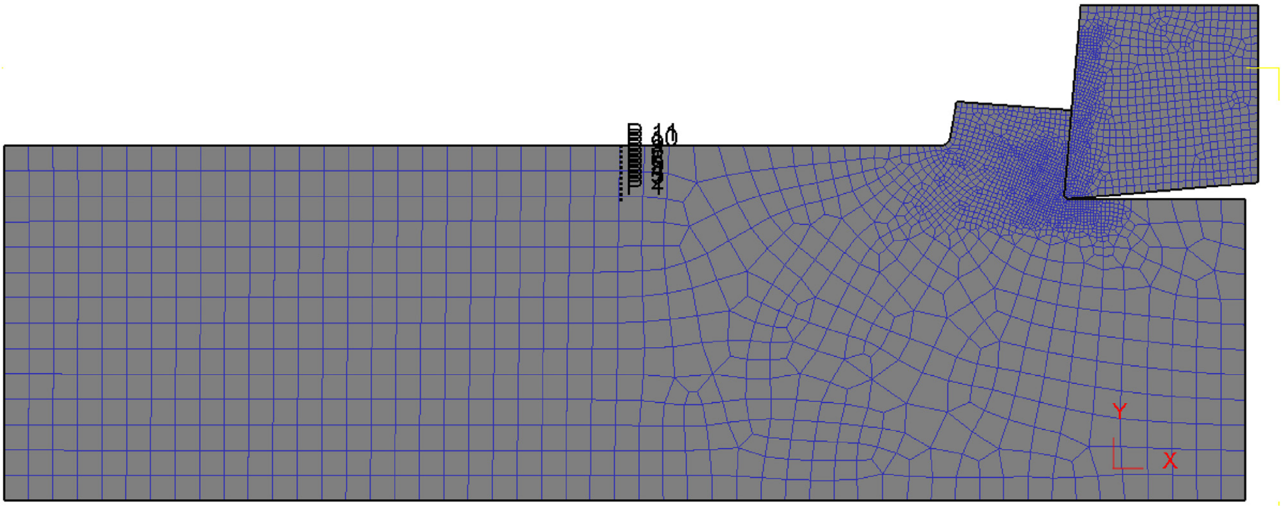

Fig. 1. Simulation setup for AISI 1045.