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Modelling the material resistance to cutting

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ABSTRACT

In the numerical simulation of machining processes, it is very widespread to use empirical dependences of the yield point of the machined material on strain, strain rate and temperature, which are known as constitutive equations.

To take of interactions between strain, strain rate and temperature into consideration as well as for describe conditions of the transition from the hardening to the softening of the material to be deformed, it is suggested that the specific deformation work in integral and differential form should be applied as characteristics of the machined material's resistance to cutting. This paper presents results of the investigations into the development of how to mathematically model the dependences of flow curves as well as of the material's yield point on temperature increase for adiabatic and isothermal deformation conditions during cutting. How temperature affects the specific deformation work and the yield point of the material to be deformed is obtained here by integrating the deduced differential equation. The layout of the deformation zones shows that it is necessary and effective to take account of the interactions regarding the models of the material resistance to deformation during cutting. The analyses also revealed that the material to be deformed in cutting hardens under almost adiabatic conditions. The material softens under isothermal conditions, which is related to the fact that deformation takes place at high temperatures in the area of the plastic contact between chip and wedge.

1. Introduction

The modelling of cutting processes with analytical and numerical methods has been gaining more and more importance recently [1–5]. Advances in the theories of metal cutting and plasticity as well as in material breakage, numerical methods and algorithms contributed to the considerable progress in the development of analytical and numerical models for different material removal processes with a minimum number of assumptions [6–9]. Regardless of the fundamental improvements in the modelling of material removal processes, there are still great differences between simulated and experimental machining characteristics yet [10,11]. The main reason for these deviations is the insufficient agreement between the simulated and the real thermo-mechanical processes occurring in the cutting zones [2,7,11]. This particularly concerns material models [12,13] since assumptions about them greatly affect the accuracy when calculating resultant forces and cutting temperature. Standardised tensile and compression tests, like e.g. in [14], served as a basis for general information about how the yield point of the material to be machined is dependent on strain, strain rate and temperature, which can be taken from well-known sources or obtained on one's own and used for modelling the machining processes.

Many researchers direct great attention to modelling the material resistance to plastic deformation at large strains, high strain rates and temperatures prevailing in the cutting process [15–19], etc. The dependence of the deformed material's yield point on strain, strain rate and temperature, which is widely known as constitutive law, is described here by an empirical function of the above-mentioned parameters. The historical development of material models with regard to cutting simulation is summarised in Table 1. At the beginning, the constitutive equation was made up with simple models such as the rigid-plastic model by von Mises and Newton's fluid (no. 1 and no. 2, Table 1). Further developments were directed towards including strain and speed hardening as well as thermal softening (no. 3 to no. 16, no. 18 to no. 21 and no. 23, Table 1). All conducted cutting tests consistently found that the chip forming process generally includes the elastic and plastic stages of material deformation as well as material breakage. In addition, these processes involve high temperatures. The thorough analysis of the experimental cutting tests showed a considerable change of the material properties in the shear zone in connection with a change in temperature and strain rate. Moreover, the cutting phenomena as well as the machining characteristics in the shear zone are changed [7]. The sensitivity of the material properties to strain rate

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Table 1
Historical view in the development of the constitutive models.

No.	Author, year of publication		Form of description
1.	v. Mises [20]		$\sigma_t = \sigma_T$
2.	Newton [20]		$\sigma_t = \mu \cdot \dot{\bar{\varepsilon}}^p$
3.	Ludwik [21]		$\sigma_t = \sigma_T + A \cdot \bar{\varepsilon}^p$
4.	Perzyna [22]		$\sigma_t = \sigma_T \cdot \left(1 + \dot{\bar{\varepsilon}}^{p*}\right)^n$
5.	Sellars and Tegart [23]		$\dot{\bar{\varepsilon}}^p = A \cdot (\sinh(a \cdot \sigma_{th}))^m \cdot e^{-\frac{Q}{R \cdot T^*}}$
6.	Litonski [24]		$\sigma_t = \sigma_T \cdot (\bar{\varepsilon}^p)^n \cdot \left(1 + B \cdot \dot{\bar{\varepsilon}}^{p*}\right)^m \cdot (1 + C \cdot \theta)$
7.	Vinh [25]		$\sigma_t = \sigma_T \cdot (\bar{\varepsilon}^p)^n \cdot \left(\dot{\bar{\varepsilon}}^{p*}\right)^m \cdot e^{-m \cdot T^*}$
8.	Johnson and Cook	Initial form [26]	$\sigma_t = (A + B \cdot (\bar{\varepsilon}^p)^n) \cdot (1 + C \cdot \ln(\dot{\bar{\varepsilon}}^{p*})) \cdot (1 - (T^*)^m)$
9.		Altan [27]	$\sigma_t = (A + B \cdot (\bar{\varepsilon}^p)^n) \cdot (1 + C \cdot \ln(\dot{\bar{\varepsilon}}^{p*})) \cdot \left(1 - (T^*)^m + a \cdot e^{-m_0\left(T^* - T_h^*\right)^2}\right)$
10.		Ee et al. [28]	$\sigma_t = (A + B \cdot (\bar{\varepsilon}^p)^n)\left(1 + C \cdot \ln\left(\dot{\bar{\varepsilon}}^{p*} + a \cdot e^{-m_1 \dot{\bar{\varepsilon}}^{p*}}\right)\right) \cdot (1 - (T^*)^m)$
11.	Usui et al. [29], Maekawa et al. [30]		$\sigma_t = \sigma_T \cdot \left[\int_{T,\ \bar{\varepsilon} \equiv (\bar{\varepsilon})} e^{-\frac{k \cdot T}{N}} \cdot (\dot{\bar{\varepsilon}}^{p*})^{-\frac{m}{N}} d\bar{\varepsilon}\right] \cdot (\dot{\bar{\varepsilon}}^{p*})^{m_1} \cdot \left(\sum_{i=1}^n A_i \cdot e^{k_i \cdot T} + B \cdot e^{k \cdot (T - T_0)^2}\right)$
12.	Klopp et al. [31]		$\sigma_t = \sigma_T \cdot \bar{\varepsilon}^n \left(\dot{\bar{\varepsilon}}^{p*}\right)^m \cdot T^{-m_1}$
13.	Zerilli and Armstrong [32]		$\sigma_t = \sigma_T + A \cdot (\bar{\varepsilon}^p)^n + B_0 \cdot e^{(-\beta_0 + \beta_1 \cdot \ln(\dot{\bar{\varepsilon}}^p)) \cdot T}$
14.	Follansbee and Kocks [33]		$\sigma_t = \sigma_T + A \cdot (\bar{\varepsilon}^p)^n + \sigma_0^* \cdot \left(1 - \left(\frac{-T \cdot k_B \cdot \ln(\dot{\bar{\varepsilon}}^{p*})}{\Delta G_0}\right)^{m_1}\right)^m$
15.	Oxley [34]		$\sigma_t = \sigma_T \cdot T_m \cdot (\bar{\varepsilon}^p)^{n \cdot T_m};\ T_m = (1 - A \cdot \ln(\dot{\bar{\varepsilon}}^{p*})) \cdot T$
16.	Hensel et al. [35]		$\sigma_{xx} = \sigma_T \cdot (\bar{\varepsilon}^p)^{n_1} \cdot e^{n_2 \cdot \bar{\varepsilon}^p} \cdot \left(\dot{\bar{\varepsilon}}^{p*}\right)^m \cdot e^{-m \cdot T^*}$
17.	Andrade et al. [36]		$\sigma = f(\varepsilon) \cdot g(\dot{\varepsilon}) \cdot h(T) \cdot H(T),\ H(T) = \frac{1}{1 - \left[1 - \left((\sigma_f)_{rec} / (\sigma_f)_{def}\right)\right] \cdot u(T)}$
18.	Marusich and Ortiz [37]		$\sigma_t = \sigma_T \cdot (A + \bar{\varepsilon}^p)^n \cdot \left(1 + B \cdot \dot{\bar{\varepsilon}}^{p*}\right)^m \cdot \sum_{i=1}^5 c_i \cdot T^i$
19.	Childs et al. [38]		$\sigma_t = \sigma_T \cdot (\bar{\varepsilon}^p)^{n(T)} \cdot (1 + A \cdot \ln(\dot{\bar{\varepsilon}}^{p*})) \cdot e^{-\left(\frac{T}{T_2}\right)^m};\ \sigma_t = \sigma_T \cdot (\bar{\varepsilon}^p)^{n(T)} \cdot \left(\dot{\bar{\varepsilon}}^{p*}\right)^{m(T)} \cdot \sum_{i=1}^n c_i \cdot T^i$
20.	El-Magd et al. [39]		$\sigma_t = (\sigma_T \cdot (A + \bar{\varepsilon}^p)^n + \eta \cdot \dot{\bar{\varepsilon}}^p) \cdot e^{-m \cdot T^*}$
21.	El-Magd and Treppman [40]		$\sigma_t = \sigma_T \cdot (\bar{\varepsilon}^p)^{n(T)} \cdot (1 + A \cdot \ln(\dot{\bar{\varepsilon}}^{p*})) \cdot e^{-\left(\frac{T}{T_2}\right)^m}$
22.	Nemat-Naser et al. [41]		$\sigma^* = g(T,\ \dot{\varepsilon}) = \hat{\sigma}\left\{1 - \left[-\frac{k}{G_0} \cdot T \cdot \left(\ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\frac{1}{q}}\right]\right\}^{\frac{1}{p}}$
23.	El-Magd et. al. [42]		$\sigma_t = \frac{\sigma_0}{\left(1 + \left(\frac{\sigma_0}{\sigma^*}\right)^v \cdot e^{\frac{T}{T^*}} \cdot \frac{\dot{\varepsilon}^*}{\dot{\varepsilon}} \cdot \varepsilon\right)^{1/v}},\ \sigma_0 = ((\sigma_T + A \cdot (\bar{\varepsilon}^p)^n) \cdot \left(\dot{\bar{\varepsilon}}^{p*}\right)^m + \eta \cdot \dot{\varepsilon}) \cdot \left(e^{-\frac{T}{T_1}} + B \cdot e^{-\left(\frac{T}{T_2}\right)^{m_1}}\right)$
24.	Calamaz et al. [43], [44] Ducobu et al. [45]		$\sigma = \left(A + B \cdot \varepsilon^n \cdot \frac{1}{\exp(\varepsilon^a)}\right) \cdot \left(1 + C \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \cdot \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \times \left(D + (1 - D) \cdot tahn\left(\frac{1}{(\varepsilon + S)^c}\right)\right)$
25.	Sima and Özel [46]		$\sigma = (A + B \cdot \varepsilon^n) \cdot \left(1 + C \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \cdot \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \times \left[D + (1 - D) \cdot \left[tahn\left(\frac{1}{(\varepsilon + p)^r}\right)\right]^s\right]$
26.	Özel and Zeren [47] Klocke et al. [49] Bäker [48]		$\sigma_t = [A + B \cdot (\bar{\varepsilon}^p)^n] \cdot \left[1 + C \cdot \ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$
27.	Umbrello et al. [50]		$\sigma(\varepsilon,\ \dot{\varepsilon},\ T,\ HRc) = B(T) \cdot (C \cdot \varepsilon^n + J + K \cdot \varepsilon) \cdot [1 + (\ln(\dot{\varepsilon})^m - A)]$
28.	Dengiur et al. [51]		$\bar{\sigma} = [A + B \cdot \varepsilon^n] \cdot \left[1 + C \cdot \ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_m - T_{room}}\right)^m\right] \cdot H(\varepsilon,\ \dot{\varepsilon},\ T) \cdot [1 - c_\eta(\eta - \eta_0)]$

and temperature shows in the primary shear zone in front of the cutting edge as well as in the secondary and tertiary shear zones.

In the last decades, the so-called inverse method for establishing the coefficients of the constitutive equation has spread due to the comparison between experimental and simulated machining characteristics (no. 26, Table 1) [70]. The Johnson-Cook model [26] is predominantly used here as constitutive equation (no. 8 to no. 10, Table 1) and is applied very widely in the simulation of various cutting processes [71]. Further developments of constitutive equations suitable for cutting processes take account of different physical phenomena during the