The Link Between Plasticity Parameters and Process Parameters in Orthogonal Cutting

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Abstract

In the present study the plasticity parameters in the Johnson Cook plasticity model are determined on the basis of process parameters in orthogonal cutting by use of inverse analysis. Previously established links between material parameters and process parameters in the cutting process such as chip thickness ratio, cutting forces, temperatures, deformation zones, is used serve as a starting point in the inverse analysis. The material AISI 4140 is simulated using the model employed in [1], the Johnson Cook parameters being changed within an interval of ±30 %. The inverse analysis is performed using a Kalman filter. The material model for the reference point is validated on the basis of the experimental results in [1], the model being shown to predict the process parameters with a high level of accuracy. The attempt is made to establish a link for materials having cutting process characteristics that are similar between certain process parameters and the Johnson Cook parameters in order to be able to predict the input parameters to FEM models using experimental data from a cutting process.

1. Introduction

Various mechanical properties such as elastic constants, flow stress and fracture stress and strain, serve as material parameters in constitutive models. These parameters and various thermo-physical constants, such as density, thermal conductivity, heat capacity, and the contact conditions at tool–chip and tool–workpiece interfaces are decisive for the reliability of the numerical models employed. The Johnson–Cook plasticity model is widely used to simulate the machining process. Orthogonal cutting using the Johnson–Cook plasticity model has been simulated by many researchers with use of FEM simulation various aspects of the machining process were investigated in this way in [2,3]. FEM simulation of manufacturing processes has been found to be a cost effective method of analysing such processes, its 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 in the use of 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 parameters of the FEM model. Achieving this would reduce considerably the efforts needed to find input parameters to FEM models.

How the material parameters used in the Johnson Cook plasticity model affect the process parameters of the cutting process, such as chip compression ratio, cutting forces, temperatures and deformation zones was investigated in [4]. For simulation of the cutting process, even in a simplified orthogonal case, one can identify about 30 different parameters of interest related to tool development and analysis of the machinability of the workpiece material. The material that was simulated was AISI 4140 where the model used in [1] being employed and the Johnson Cook plasticity parameters being changed within the interval of ±30 %. The present study was carried out to obtain a better understanding of how the Johnson Cook parameters should be changed within

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a material group having cutting process parameters that are similar.

In the work reported on here, the variation of the process parameter obtained is studied and a polynomial function of the fourth order being interpolated. An inverse analysis using a Kalman filter is performed in order to determine the plasticity material parameters in the Johnson-Cook model. To validate the method and the estimated JC-parameters, a new FEM simulation of the cutting process was carried out, the process parameter obtained being compared with the reference values.

2. Inverse Analysis

The Kalman filter, [5] is an inverse analysis technique used in many engineering applications. The algorithm is utilized here to estimate five unknown material parameters in the Johnson-Cook plasticity model on the basis of four experimentally measured cutting process parameters. In the formulation employed, the five unknown parameters are represented in state vector form as:
\[ \mathbf{x}_t = (A_0, B_0, C_0, n_0, m_0) \]

At time t=0 the initial estimates are assigned as:
\[ \mathbf{x}_0 = (A_0, B_0, C_0, n_0, m_0) \]

The equation that follows is used to make subsequent estimates:

\[ \mathbf{x}_t = \mathbf{x}_{t-1} + \mathbf{K}_t [\mathbf{d}_{x,215\%} - \mathbf{d}_t(x_{t-1})] \quad (1) \]

\[ \mathbf{K}_t \] is the Kalman gain matrix, \[ \mathbf{d}_{x,215\%} \] is the vector containing the process parameters that are measured and \[ \mathbf{d}_t(x_{t-1}) \] is the vector containing the process parameter computed unknown for the estimates made for the previous increment. The Kalman gain matrix is computed as:

\[ \mathbf{K}_t = \mathbf{P}_t \frac{\partial \mathbf{d}_t}{\partial \mathbf{x}_t} \mathbf{R}_t^{-1} \]

\[ \mathbf{P}_t = \mathbf{P}_{t-1} - \mathbf{P}_{t-1} \left( \frac{\partial \mathbf{d}_t}{\partial \mathbf{x}_t} \right)^T \left( \frac{\partial \mathbf{d}_t}{\partial \mathbf{x}_t} \right) \mathbf{R}_t \]

The Kalman gain matrix is multiplied with the differences between the simulated and the computed process parameters to provide corrections to the unknown-state material parameters. For five material and four process parameters, the size of the Kalman gain matrix is 5x4, \( \frac{\partial \mathbf{d}_t}{\partial \mathbf{x}_t} \) being a 4x5 matrix containing the gradients of \mathbf{d}_t with respect to the material parameters. In addition, \( \mathbf{P}_t \) is the ‘simulation covariance matrix’, related to the range of the unknown material parameters at increment t, and \( \mathbf{R}_t \) is the ‘error covariance matrix’, related to the size of simulated error. \( \mathbf{P}_t \) is updated at each step, whereas \( \mathbf{R}_t \) is prescribed at the beginning of the iteration. Since the convergence rate of the Kalman algorithm is sensitive to the values of \( \mathbf{P}_t \) and \( \mathbf{R}_t \), it is essential that these two matrices be properly assigned. The initial simulation covariance matrix \( \mathbf{P}_0 \) and the error covariance matrix \( \mathbf{R}_t \) are set to:

\[ \mathbf{P}_0 = \begin{pmatrix} (\Delta A)^2 & 0 & 0 & 0 & 0 \\ (\Delta B)^2 & 0 & 0 & 0 & 0 \\ (\Delta C)^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} 
\]

\[ \mathbf{R}_t = \begin{pmatrix} P^2 & 0 & 0 & 0 & 0 \\ 0 & \lambda_t^2 & 0 & 0 & 0 \\ 0 & 0 & \nu_{el}^2 & 0 & 0 \\ 0 & 0 & 0 & \theta_t^2 & 0 \end{pmatrix} \quad (3) \]

Here, \((\Delta A)^2, (\Delta B)^2, \ldots, (\Delta M)^2\) denotes the predicted ranges of the unknown material parameters. In the current analysis the diagonal components of \( \mathbf{R}_t \) are chosen on the basis of the simulated process parameters. The Kalman filter procedure was implemented in MATLAB. The inverse analysis requires certain knowledge regarding the relationship between the material parameters and the process parameters. The link between these was established in [4], this link also being presented in section 5.1 here.

3. Material Model

The workpiece was modelled as consisting of the AISI 4140 material, a cemented carbide material being used for the tool. The general thermal and mechanical properties are presented in detail in Table 1. Since the specific heat of the workpiece material is highly temperature-dependent a temperature-dependent model was employed, presented in [1].

Table 1. General thermal and mechanical properties of the material.

| Properties | Workpiece | Tool | Units |
|------------|-----------|------|-------|
| Density    | 7850      | 12000| [kg m^-3] |
| Young's modulus | 219 | 540 | [Gpa] |
| Poisson's ratio | 0.29 | 0.22 | |
| Thermal expansion | 13.7 | 4.7 | [μm m^K^-1] |
| Melting temperature | 1820 | - | [K] |
| Bulk temperature | 300 | 300 | [K] |
| Thermal conductivity | 42 | 40 | [W m^-1 K^-1] |
| Specific heat capacity | - | 203 | [J kg^-1 K^-1] |

3.1. Constitutive law

The material model employed here is the Johnson Cook plasticity model, developed by Johnson and Cook. This constitutive relationship is commonly employed in modelling orthogonal cutting with use of FEM, since due to its being strain rate and temperature dependent it has a strong effect on the strain/stress relationship in the machining process. The constitutive law is given by:

\[ \sigma = [A + B(\varepsilon^p)^n][1 + C \ln (\frac{\varepsilon^p}{\varepsilon^p_{eq}})][1 - \theta^{-m}] \quad (4) \]

\[ \theta^* = \frac{\theta - \theta_0}{\theta_{eq} - \theta_0} \quad (5) \]

where \( \sigma \) is the equivalent stress, \( \varepsilon^p \) is the equivalent plastic strain, \( \varepsilon^p_{eq} \) is the equivalent plastic strain rate, \( \theta_{eq} \) is
the reference strain rate, $A$ is the initial yield stress, $B$ is the hardening modulus, $C$ is the strain rate dependency coefficient, $n$ is the strain-hardening exponent, $m$ is the thermal softening coefficient, $\theta$ is the process temperature, $\theta_{\text{mel}}$ is the melting temperature and $\theta_0$ is the bulk temperature. The plasticity parameters are presented in Table 2.

Table 2. Johnson-Cook plasticity model parameters.

| A [Mpa] | B [Mpa] | C   | n  | m  |
|---------|---------|-----|----|----|
| 595     | 580     | 0.023 | 0.133 | 1.03 |

3.2. Chip separation criteria

In the present study the Johnson Cook damage law is used to model the chip separation. The cumulative damage law is given by

$$D = \sum \left( \frac{\Delta e_P}{\Delta e_f} \right)$$

where $D$ is the damage parameter, $\Delta e_P$ is the increment of the equivalent plastic strain and $\Delta e_f$ is the equivalent strain at failure. According to the Johnson-Cook model, $\Delta e_P$ is updated at every load step and $\Delta e_f$ is expressed by

$$\Delta e_f = \left[ D_1 + D_2 \exp \left( \frac{x}{D_3} \right) \right] \left[ 1 + D_4 \ln \left( \frac{\dot{\varepsilon}_p}{\varepsilon_0} \right) \right] \left[ 1 + D_5 \theta' \right]$$

where $\dot{\varepsilon}_p$ is the equivalent plastic strain rate, $\varepsilon_0$ is the reference strain rate, $P/\sigma_y$ is ratio of the hydrostatic pressure to the equivalent stress and $\theta'$ is defined by Eq. (5). Failure occurs when the damage parameter $D$, as given in Eq. (6) reaches 1. When this condition is fulfilled within an element, the stress component is set to zero and remains zero for the rest of the calculation. The damage parameters are presented in Table 3.

Table 3. The Johnson-Cook damage model parameters.

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|-------|-------|-------|-------|-------|
| 1.5   | 3.44  | -2.12 | 0.002 | 0.1   |

3.3. Tool-chip interface contact

The contact interaction in machining has two distinct zones: sliding and sticking friction. The sticking friction appears around the tool tip, due to the high pressures in that region. Since there the frictional stress is greater than the yield stress of the material, deformation occurs inside the workpiece material instead of sliding at the contact surface. For the rest of the contact interface sliding friction takes place. This has been modelled by use of Coulomb's friction law, setting an upper bound to the frictional force and using the region in which the maximum frictional stress is produced to model the sticking region, which is defined by

$$f_f = \mu \sigma_n \text{ when } \mu \sigma_n < \tau_{\text{max}}$$

$$f_f = \tau_{\text{max}} \text{ when } \mu \sigma_n \geq \tau_{\text{max}}$$

where $\sigma_n$ is the normal stress along the tool-chip interface, $\mu$ is the friction coefficient, $f_f$ is the frictional stress and $\tau_{\text{max}}$ is the maximum value of the frictional stress, $\tau_{\text{max}}$ is assumed to be equal to the yield shear stress of the material $\tau_{\gamma}$, where $\tau_{\gamma}$ is calculated as $\tau_{\gamma} = \sigma_{\gamma}/\sqrt{3}$, where $\sigma_{\gamma}$ and $\sigma_{\gamma}$ are the yield stress values of the material for simple shear and under tension stress, respectively, $\sigma_{\gamma}$ being defined by the parameter $A$ in the form of the Johnson Cook model employed. The friction coefficient is set to 0.4. Since the mechanisms behind the friction problem are not fully understood this friction model has been employed for reasons of simplicity.

3.4. Heat generation and heat transfer between the tool and the chip

There are two sources of heat generation in the machining material: plastic deformation and friction. Most of the plastic deformation energy is converted to heat. In the present study the percentage was taken as 90%, this has been used in previous studies. Since the heat generated by friction is assumed to be fully absorbed by the material, the fraction of the heat generated by friction is set to 1.0, this having been used in previous studies. The percentage of the deformation energy is probably closer to 100% than to 90% since the elastic part is close to being negligible. In simulating the heat flow between the tool and the workpiece a thermal boundary condition was defined.

The heat conduction between the tool and the workpiece is pressure-dependent. The heat conduction coefficient $h$ is defined as a function of the pressure in accordance with Table 4.

Table 4. The pressure-dependent heat conduction coefficient.

| $P$ [MPa] | 0 | 30 | 180 | 300 | 420 | 600 |
|-----------|---|----|-----|-----|-----|-----|
| $h$ [kW/m²K] | 5 | 18 | 87 | 222 | 410 | 500 |

The conductive heat transfer between the contact surfaces is defined as $q = h(P)(\theta_{\text{A}} - \theta_B)$, where $q$ is the heat flux per unit of area crossing the interface from point A on the one surface to point B on the other, $\theta_A$ and $\theta_B$ being the temperatures of the points on the surfaces, and $h(P)$ being the heat conduction coefficient.

4. Finite Element Model

The orthogonal cutting process was simulated by use of a 2D model in ABAQUS/Explicit v6.11-3, a fully coupled thermo-mechanical analysis being performed. The ALE formulation with use of Lagrangian boundary conditions was employed in this model. The workpiece
length was taken to be 5 mm and its height to be 2 mm. The cutting tool had a clearance angle $\alpha$ of 5°, a rake angle $\gamma$ of 0°, an edge radius of $r_e = 50 \, \mu\text{m}$, and a height and length of 2 mm, the cutting speed $v_c$ being set to 260 m/min. The uncut chip thickness $h_1$ was set to 0.1 mm for all of the simulations.

5. Results

Of the approximately 30 results parameters obtained in an FEM simulation 4 of the parameters were selected as input to the inverse Kalman analysis. These input parameters were selected due to the resources required for determining them with the required accuracy, though experimental studies being at a minimum.

The process parameters that were selected for use in constructing the polynomials in the Kalman filter were the following:

- Primary cutting force, $(F_c)$
- Chip thickness ratio, $(\lambda_h)$
- Maximum strain in the 3rd deformation zone, $(\gamma_{III})$
- Temperature after the primary zone, $(\theta_1)$

The variation found in each of these parameters with use of the Johnson Cook plasticity parameters is presented in the subsection that follows. The data for each process parameter, shown as a function of the Johnson Cook plasticity parameters was fitted by use of a 4th degree polynomial. These polynomials make up the solution path of the Kalman filter. "Ref" in Fig 1-4 represents the output data given by the reference material.

5.1. Variation of the process parameters variation with the Johnson Cook plasticity parameters

The cutting force was obtained as the sum of the contact forces of all of the nodes in the interaction area that were active. Fig 1 shows how the primary cutting force varied with the five different plasticity parameters.

Since the chip compression ratio varied somewhat within each simulation, no mean value over the steady state phase was determined. Rather such a value was obtained for one specific frame within the steady state phase. Fig 2 shows how the chip compression ratio varies for each of the five different plasticity parameters.

The maximum strain for the 3rd deformation zone was determined as the mean of the maximum strains on the newly formed surface. Fig 3 shows how the maximum strain in the tertiary zone varies with the five different plasticity parameters.
The plastic deformation and the friction lead to a rise in temperature in the workpiece material primarily in the deformation zones. The workpiece material is subjected to a rapid increase in temperature as it passes through the primary deformation zone. The temperature $\theta$ is taken as in each case the mean of the temperatures in the middle of the chip just after it has passed through this zone. Fig 4 shows how the temperature in the chip just after it has passed through the primary zone varies for each of the five different plasticity parameters.

5.2. Solution path of the Kalman filter

As a verification of the Johnson–Cook parameters that are the output of the Kalman filter the result vector $\mathbf{x}_0$ for the FEM simulations $A - 15\%$, $B + 15\%$, $C + 15\%$, $n - 15\%$ and $m + 15\%$, were taken as inputs to the filter. Since the Kalman filter minimizes the Euclidean norm $||\mathbf{x}_0 - \mathbf{x}_i||$, here, the tolerance for this norm was that it should be less than 0.01. The solution path for the chip compression ratio, $\lambda_c$ and maximum strain in zone III, $\varepsilon_{III}$ for vector $\mathbf{d}_{B+15\%}$ are shown in Fig 5. The initial values for the vector $\mathbf{d}_i$ are the process parameters for the reference material, $\mathbf{d}_0$. The Johnson Cook parameters that the Kalman filter gave as output are shown in Table 5. As can be seen here the Johnson Cook parameters given by the Kalman filter are not the same as those used in the FEM simulations, that produced the process parameter vectors $\mathbf{d}_{B\pm15\%}$. This indicates there to be no unique solution for any of the sets of process parameters, a result which appears reasonable since an underdetermined system is involved.

5.3. Validation

As a validation of the Johnson Cook parameters that the Kalman filter produced as outputs $\mathbf{x}_{B+15\%}$, these parameters were used in the material model of the FEM model which produced the process parameters, $\mathbf{x}_{B+15\%}$ as shown in Fig 6. These $\mathbf{x}_{B+15\%}$ were then compared with the process parameters given by FEM in the simulations: $\mathbf{x}_{A-15\%}$, $\mathbf{x}_{B+15\%}$, $\mathbf{x}_{C-15\%}$, $\mathbf{x}_{m+15\%}$ and $\mathbf{x}_{n-15\%}$. As can be seen in Table 6 there is rather close agreement between the process parameters given by the two sets of Johnson Cook parameters. This validates the Kalman filter being able to predict how the Johnson Cook parameters change in the material model in materials belonging to the same material group as the reference material.
6. Conclusions

The study shows it to be fully possible, through employing an inverse procedure based on use of a Kalman filter, metal cutting experiments can be used to determine the input to FEM simulations in the form of JC-parameters. The principle involved assumes there to be a reference simulation of a well-known workpiece material belonging to the same material group and showing similar metal cutting behaviour to have been carried out; in this connection see the principles employed in the polar diagrams used for determining potential machinability [6,7]. The robustness of this method has not yet been examined for experimental data from any other material in the same material group. Although the study shows the method to be able to predict JC-parameters this concerns degree accuracy of only about 7.6 % of the process parameters that have been measured experimentally.

Acknowledgements

This research is a part of the ShortCut research project financed by the Swedish Foundation for Strategic Research SSF. It is also a part of the strategic research program of the Sustainable Production Initiative SPI, involving cooperation between Lund University and Chalmers University of Technology. The authors would like to thank Seco Tools for providing the necessary tools.

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