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Inverse Identification of the Constitutive Equation of Inconel 718 and AISI 1045 from FE Machining Simulations

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Abstract

Until now, the progress, which was achieved in the field of computer technology, could not be used to broadly introduce FEM-modeling techniques in the machining sector of the manufacturing industry. Despite the potentials of modeling cutting processes with the FEM, such as predicting tool loads and chip forms, there are obstacles, which hinder a successful adoption. One of the most challenging aspects is the modeling of the viscoplastic workmaterial behaviour during machining processes. In the past expensive and time-consuming experiments like the Split-Hopkinson Pressure Bar Test were used to obtain material data at the extreme conditions of cutting (T close to T_{melt}, strains ~ 5, strain rates > 10^6). New, inverse methods of identifying the flow stress data are faster, easier to execute and potentially more accurate.

This paper applies a new methodology to inversely identify the flow stress data in orthogonal cutting, which was originally developed at the ISM of the University of Kentucky, USA, and the WZL of RWTH Aachen University, Germany. The derived method is applied to identify the flow stress data of Inconel 718 and steel AISI 1045 in order to create 2D FE-models of the orthogonal cutting process for various cutting conditions. The models are validated by experiments on a specially designed test set-up on a broaching machine, which is distinguished by other orthogonal cutting tests by the straight geometry of the workpiece, which allows a direct comparison with 2D FE-simulations. The experiments include highspeed-filming the chip formation, measuring the cutting forces and temperatures.

1 Introduction

For FE-simulations of machining processes modeling the visco-plastic material behavior plays a major role since the prediction of many cutting results can be traced back to the quality of the applied flow stress data. A common way to model the yield stresses is to apply constitutive relationships. A great vararity of these models exists in the literature, which consider different influences on the flow stress. The most important influences are strain, strain-rate and temperature. Johnson-Cook (JC) derived a mathematically relatively simple expression, which is broadly used in the literature for the FE-simulation of machining processes, see equation 1 [1], [2]:

$$\sigma_{yld} = \left[A + B \cdot \varepsilon^n\right]\left[1 + C \cdot \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \quad (1)$$

,where ε stands for the strain, $\dot{\varepsilon}$ for the strain-rate and T for the temperature.

The JC constitutive equation, and any other equation as well, can be applied to a certain material by determining the constants in the equation for certain intervals of ε, $\dot{\varepsilon}$ and T (see A, B, n, C, m in equation 1). $\dot{\varepsilon}_0$ and T_0 are reference values for strain-rate and temperature, which were applied during the identification of the strain hardening behavior of the material (term 1 in equation 1). Often quasi static conditions at room temperature are considered ($\dot{\varepsilon}_0$ = 0,001; T_0 = 20 °C).

The methodology of identifying the constants plays an important role in the material modeling of FEM-machining simulations [3], [4]. The methodologies available in the literature can be divided into experimental, analytical and numerical approaches. Experimental material tests, like the Split-Hopkinson-Pressure-Bar-Test (SHPBT) are very time-consuming and expensive, since the material has to be analyzed at extreme strain-rates and temperatures ($\dot{\varepsilon}$ up to 10^6 /s, T/T_{melt} up to 0,9, [5]). In addition the strain-rates, which can be realized by the SHPBT do not exceed 10^4 /s, thus creating inaccuracies by extrapolating the strain-rates to the required intervals. Numerical approaches, which determine the flow stress data inversely from machining experiments are promising since they can model the material behavior under the needed conditions in an fast and efficient way.

2 Description of the proposed Methodology of Identifying the Johnson-Cook Material constants

The proposed methodology of identifying the flow stress data systematically compares the material constants, which are implemented into a FE-model of a machining process with experimentally obtained cutting results. The constants, which result in the correct prediction of the cutting forces and chip geometries are identified by interpolation. Since the proposed methodology is inverse and depends on machining tests, its robustness with respect to stochastic variations of the experimental data has to be considered. The generated material models are based on single sets of experimental data and thus cannot incorporate variations in the measurements, which is a characteristic of all inverse methodologies. In order to minimize this uncertainty, it is recommended to conduct multiple repetitions of the experiments.

Constants A, B and n in equation (1) are obtained from quasi static tensile/upsetting tests, since they describe the strain hardening behaviour. The method of least squares is applied in order to fit A, B and n to the experimental evolution of the true stress-true strain curves.

For C and m, which model the impact of strain-rate and temperature, different values are implemented into the FE-model. The determined relationships between the material constants and the predicted cutting forces and chip geometries are used to interpolate values for C and m in order to minimize the error between simulation and experiment.

In case of serrated chip formation, an additional damage criterion has to be identified, which considers the formation of adiabatic shear bands in materials with low thermal conductivities, like superalloys. Cockcroft and Latham developed a criterion, which is based on the consumed plastic energy [6]:

$$D = \int_{\varepsilon} \max(\sigma_I, 0) \cdot d\varepsilon \qquad (2)$$

When a critical value D_{crit} is reached, the flow stress is reduced to a lower value p, which is expressed as percentage of the original flow stress. This decrease of flow stress results in the characteristic serrated chip geometry and additionally affects the obtained cutting forces, see Fig. 1. The determination of D_{crit} and p is conducted analog to the procedure for C and m. Since the constants are identified according to the experimental cutting forces and additionally to the chip geometry, multiple solutions will be identified. An objective algorithm is necessary to calculate the solution, which is able to correctly calculate all cutting results simultaneously.
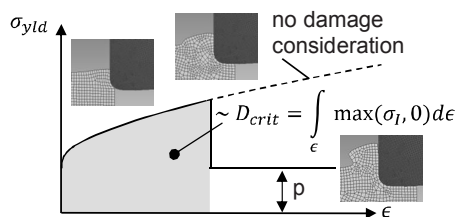

Fig. 1. The Cockcroft & Latham damage criterion for the prediction of serrated chip formation

In the following the methodology is applied for the identification of the JC constitutive for AISI 1045 (continuous chip formation) and Inconel 718 (serrated chip formation) with the damage criterion of Cockcroft and Latham

3 Machining Experiments

For the identification of the constitutive equations for AISI 1045 and Inconel 718 using the proposed methodology, experimental cutting forces and chip geometries have to be obtained. Fig. 2 shows the set-up for the orthogonal cutting tests on a broaching machine. The linear geometry of the workpieces allows an exact comparison to the 2D FE-simulations. The cutting forces are measured by a piezoelectric dynamometer (Kistler 9255B), which was constructed for this particular broaching machine at the WZL of the RWTH Aachen University [7]. The chip formation process is filmed by a high speed camera (Kistler Visionresearch Phantom v7.3; 10000 fps at 640x480) and the chip geometries are analyzed by optical microscopy. Temperatures are measured by a 2-color-pyrometer (WSA Fire 2) through a hole from beneath the machines surface (see Fig. 11).
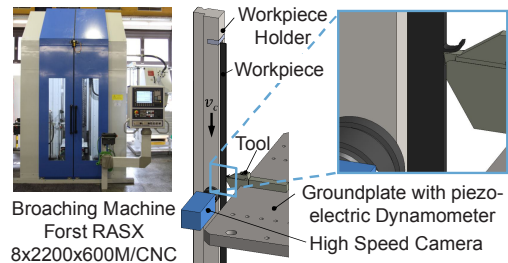

Fig. 2. Experimental Set-Up for Orthogonal Cutting Tests

The workpiece dimensions are 50 mm x 35 mm x 3 mm. The tools are uncoated cemented carbide inserts (WC-6CO). The investigated cutting conditions are shown in Table 1. All tool rake angles are 0°, all tool flank angles are 7° and the cutting edge radii are $r_\beta = 30$ μm. The tool rake faces are flat, no chip formers are used.

For Inconel 718 chip serration is recorded. All machining results are discussed in the experimental validation in section 4.

Table 1. Conducted Orthogonal Cutting Experiments

Material	Feed Rate f/mm	Cutting Speed v_c/ m/min
AISI 1045	0,1	50
	0,2	100
	0,3	
	0,4	
Inconel 718	0,02	20
	0,05	5
		10
		20
		30
		40
	0,075	10
		20
		40
	0,1	20

4 Application and validation of the proposed Methodology for Inconel 718 and AISI 1045

4.1 FE-Model

The proposed methodology of identifying the constitutive material behavior during machining processes is inverse and requires a FE-process model. In this work the commercial FE code Deform 2D was utilized, which is based on the
implicit updated Lagrangian formulation. The tool was assumed to be rigid while workpiecematerial is modeled to be visco-plastic. Special attention is paid to the applied friction model in the tool-workpiece interface because the friction has a major influence on the calculated cutting forces and chip geometries. Since the calculated forces are used to calibrate the material constants, the utilized friction model has to be of high quality. In this work a hybrid friction model is used, which considers the relative velocity between both friction partners. Puls developed both an extended hybrid friction model and an experimental methodology to determine the coulomb friction coefficients in the tool workpiece interface, which are used in this work and which are shown in Fig. 3 [8].
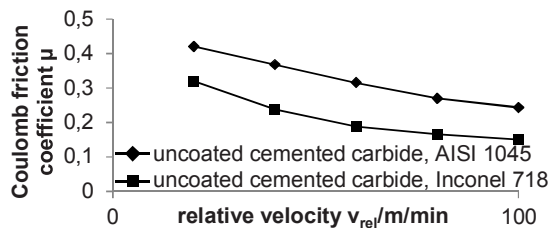

Fig. 3. Implemented Coulomb friction coefficients in the hybrid friction model for uncoated cemented carbide and AISI 1045 and Inconel 718 [8]

The frictional stresses are limited by the shear friction part in the hybrid model to be equal to the material's flow stress ($m_{shear} = 1$).
The thermal properties of the cutting material were taken from the literature, while the thermal properties of AISI 1045 and Inconel 718 are taken from the Deform 2D library [9].

4.2 Identification of the Johnson Cook Constitutive Equation for AISI 1045 and Inconel 718

For AISI 1045 five constants have to be identified: A, B, n, C and m (equation 1). For Inconel 718, due to the recorded chip serration, in addition the Cockcroft & Latham damage criterion has to be identified (D_{crit}, p, equation 2).

AISI 1045, normalized

A, B and n of AISI 1045 were taken from compression test data available in the literature [10]:

A = 546 MPa; B = 487 MPa; n = 0,25.

For the determination of C and m (equation 1) a full factorial simulation schedule was applied in order to identify the impact of C and m on the cutting forces and chip thickness, see Fig. 4. Each interception point between experiment and FE-model is a solution for the correct prediction of the regarded cutting result on the y-axis. It

can be seen that the impact of C and m on the cutting forces and the chip thickness is almost linear, so that for the following analysis two variations in C and m are regarded to be sufficient.
In order to calculate one final solution for A, B, n, C and m, the determined interception points have to be evaluated based on their distance to each other since the final solution is supposed to correctly predict all cutting results at the same time. The final solution is the average value of the combination of solutions for Fc, Ff and h, which lies together the closest. The numerical distance between the solutions is expressed by the average variation (avg var) in C and m. The combinations of solutions are ranked (the lower the difference, the lower the rank). The ranks in C and m are summed up for all combination and the combination with the lowest over-all-rank suits best for the determination of the final solution (see Table 2).
From Table 2 it can be seen that the identified values for C and m of combination 6 lie together the closest. Accordingly, the average values of C and m are taken to calculate the final solution for AISI 1045:
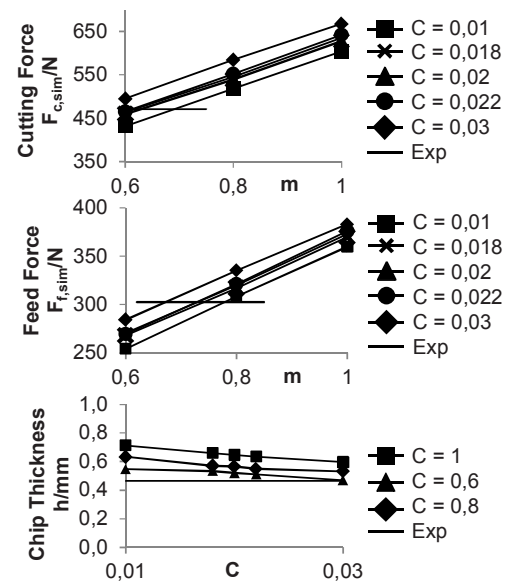
m = 0,631; C = 0,027.

Fig. 4. Simulated cutting results for AISI 1045 under variation of C and m in the Johnson-Cook equation (v_c = 100 m/min, f = 0,2 mm)

Table 2. Determination of the best solution for the prediction of F_c, F_f and h for AISI 1045

#	m_{Fc}; m_{Ff}; m_h	C_{Fc}; C_{Ff}; C_h	avg var m	Rank m	avg var C	Rank C	Sum of Rank	Over-All-Rank
1	0,691; 0,781; 0,6	0,01; 0,01; 0,03	0,061	6	0,009	4	10	7
2	0,691; 0,728; 0,6	0,01; 0,02; 0,03	0,049	4	0,007	3	7	5
3	0,691; 0,672; 0,6	0,01; 0,03; 0,03	0,036	2	0,009	4	6	3
4	0,620; 0,781; 0,6	0,02; 0,01; 0,03	0,076	8	0,007	3	11	8
5	0,620; 0,728; 0,6	0,02; 0,02; 0,03	0,052	5	0,004	2	7	4
6	**0,620; 0,672; 0,6**	**0,02; 0,03; 0,03**	**0,028**	**1**	**0,004**	**2**	**3**	**1**
7	0,542; 0,781; 0,6	0,03; 0,01; 0,03	0,093	9	0,009	4	13	9
8	0,542; 0,728; 0,6	0,03; 0,02; 0,03	0,070	7	0,004	2	9	6
9	0,542; 0,672; 0,6	0,03; 0,03; 0,03	0,045	3	0	1	4	2

Inconel 718, aged

The same procedure is applied for the identification of the JC relationship and the Cockcroft & Latham damage criterion for Inconel 718.

For modeling the strain hardening behavior (parameters A, B, n in equation 1) an existing quasi-static flow curve at room temperature was taken from Issler [11]. Isslers material differs from the analyzed material in hardness. DIN EN ISO 18265:2003 is used in order to shift Isslers flow curve to the measured hardness of the investigated charge (46.1 HRC). After converting the technical stresses and strains to the real ones the method of the least squares was applied to approximate A, B and n for Inconel 718 with 46.1 HRC:

$$A = 1485 \text{ MPa}, B = 904, n = 0{,}777.$$

For the identification of C and m the applied values of D_{crit} and p of the Cockcroft & Latham damage criterion have to be considered because they have a strong influence on the calculated cutting forces and chip geometries. Accordingly, the full factorial simulation schedule consists of the variation of C, m, D_{crit} and p. Considering the almost linear evolution of the cutting results with respect to C and m for AISI 1045 (see Fig. 4) two factor levels are chosen. This simplification has to be justified in the following validation of the methodology.
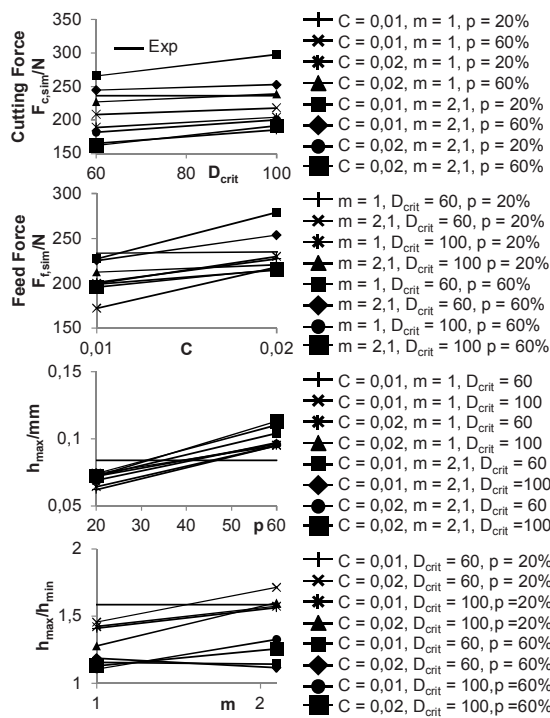

Fig. 5. Simulated cutting results for In 718 under variation of C, m in the Johnson-Cook equation and D_{crit}, p in the Cockcroft & Latham damage criterion

Analog to Fig. 4, Fig. 5 shows the simulated cutting results for Inconel 718 under variation of C, m, Dcrit and p. Table 3 shows the determination of the best solution for the JC relation and the C&L damage criterion for Inconel 718. The values for C, m, D_{crit} and p, which result in the correct prediction of the individual cutting results (y-axis in Fig. 5) are not shown for reasons of clarity. It can be seen that solution combination 81 lies together the clos-

est, so that the final C, m, D_{crit} and p are calculated as the average values of combination 81:

$$m = 1{,}689; C = 0{,}015; D_{crit} = 97{,}8; p = 43{,}13 \text{ \%}.$$

Table 3. Determination of the best solution for the prediction of F_c, F_f, h_{max} and h_{max}/h_{min} for Inconel 718

#	avg var m	Rank m	avg var C	Rank C	avg var D_{crit}	Rank D_{crit}	avg var p	Rank p	Sum of Rank	Over-All-Rank
1	0,412	4	0,005	12	17,805	4	16,87	12	32	20
2	0,406	3	0,005	12	13,903	3	16,87	12	30	18
3	0,422	6	0,004	7	13,903	3	16,87	12	28	16
⋮										
81	0,393	2	3e-4	1	3,29	1	15	8	12	1
⋮										
160	0,586	12	0,006	15	17,81	4	15,25	9	40	28

4.3 Validation of the proposed Methodology

The identified JC constitutive equations of AISI 1045 and Inconel 718 were implemented into the FE-model for different cutting conditions with varying cutting speeds and feed rates. For Inconel 718 the identified Cockcroft & Latham damage criterion was as well implemented. In the following the comparisons between experimental and numerical results are shown with respect to the cutting force components (F_c, F_f) the chip geometries (h for AISI 1045, h_{max} and serration ratio h_{max}/h_{min} for Inconel 718) and the cutting temperatures.

Cutting Forces

Fig. 6 shows the measured and predicted cutting force components for AISI 1045.
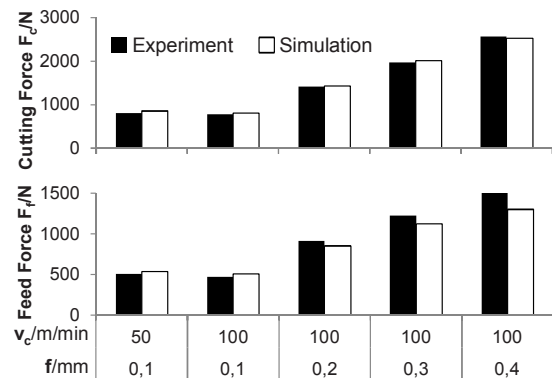

Fig. 6. Experimental validation with respect to the cutting forces for AISI 1045

Fig. 7 shows the measured and predicted cutting force components for Inconel 718.

The average error between the experimental and numerical data is ca. 10 %. Considering the wide range of applied cutting speeds (~strain rates) and feed rates (~strains) the proposed methodology of identifying constitutive equations shows excellent results with respect to the predicted cutting forces.
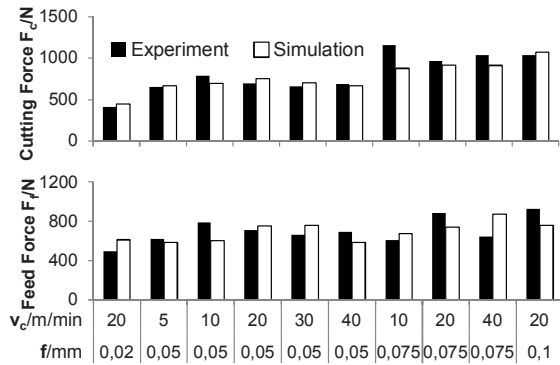
Fig. 7. Experimental validation with respect to the cutting forces for Inconel 718

Chip Geometries

The orthogonal machining tests with AISI 1045 revealed continuous chip formation for the range of studied cutting conditions. Thus, the chip thickness is used to validate the chip geometry in the FE-model for AISI 1045, Fig. 8.
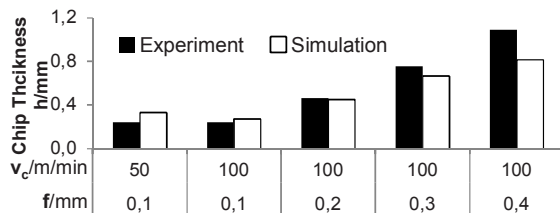

Fig. 8. Experimental validation with respect to the chip thickness for AISI 1045
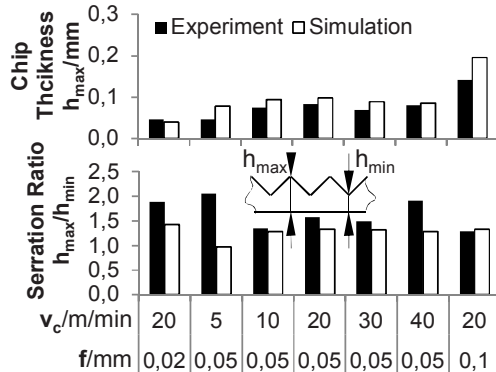

Fig. 9. Experimental validation with respect to the serrated chip geometry for Inconel 718

The serrated chip geometries, which were detected for Inconel 718 are considered in the FE-model by the Cockcroft & Latham damage criterion. For the objective experimental validation of the model the serrated geometry is described by the maximum chip thickness h_{max} and the serration ratio h_{max}/h_{min}. The comparison of the predicted and measured results are shown in Fig. 9.

It can be seen that the chip dimensions could be predicted in close agreement to the experiments. Concerning the chip formation process the computation model verifies the experimental results very closely as well, see Fig. 10).
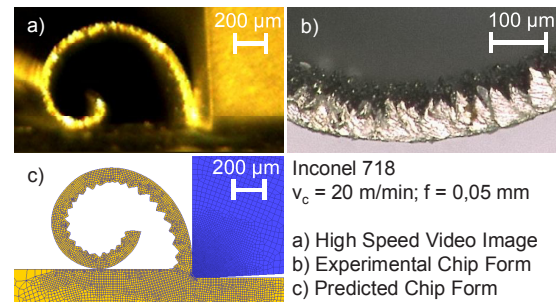

Fig. 10. Experimental and calculated chip formation for Inconel 718

Cutting Temperatures

Cutting temperatures were measured by a 2-color-pyrometer through a hole from beneath the machined surface. The measured and predicted temperatures are compared in Fig. 11.
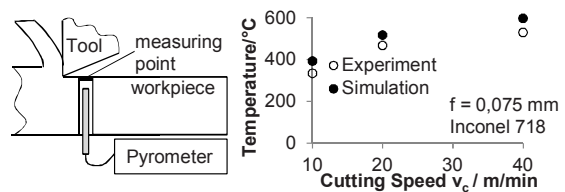

Fig. 11. Measured and predicted temperatures

It can be seen that the calculated temperatures are in close agreement to the experimental results. Thus, the proposed methodology of identifying the JC and CL relationships could be validated also with respect to the cutting temperatures.

5 Conclusion

An inverse methodology of identifying the constitutive equations and damage criteria for FE-modelling of machining operations was presented. The method was applied and validated for orthogonal cutting of AISI 1045 and Inconel 718.

The proposed approach systematically compares cutting results from machining tests with simulation results and interpolates those constitutive material parameters, whose application in an FE-model minimizes the error to the experiments. An objective algorithm identifies physically reasonable solutions from the solution space of material constants. Both cutting force components (Fc, Ff) and the chip geometry (h, serration ratio h_{max}/h_{min}) are considered by the algorithm.

The method was successfully applied and validated on steel AISI 1045 and Inconel 718 for various cutting speeds and feed rates. The measured and predicted cutting forces, chip geometries and temperatures are in close agreement.

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