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Simulative investigations on different friction coefficient models

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Abstract

This work aims on the comparison of different friction coefficient models depending on the variable parameters including sliding speed, temperature, contact pressure based on experimental friction measurements. The impact on the temperature distribution to predict phase transformations during turning of AISI 4140 for dry and minimum quantity lubricated machining is investigated for each parameter separately. Based on these results an optimized friction model is built up. The results are validated with experiments.

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Keywords: Friction, Modelling, Finite element method

1. Introduction

The stresses in the primary and secondary shear zone cause plastic deformation in the workpiece and the chip. Consequently, the thermal and mechanical load of the workpiece highly interacts with the friction effects between the tool and the emerging chip. According to this circumstance and the shape of the resulting chip, the sliding speed varies between the tool-chip interface [1]. Reaching higher temperatures during the cutting process softens the elastic-plastic material behavior and influences the cutting forces. In case of the prediction of machining characteristics like the temperatures, forces or phase transformations an adequate modelling of the friction behavior becomes essential in chip formation simulations.

Within the last decades, many different friction coefficient testing methods and friction models were introduced. Arrazola et al. investigated the adequacy of constant Coulumb's friction coefficients in simulations. The results show a big discrepancy in feed force measurements compared to experimental data [1]. Puls et al. developed an orthogonal test mechanism based on broaching. In this developed setup, the cutting tool is placed with a high rake angle to suppress the chip formation. A variation of the normal force and the sliding speed were used to measure different temperatures and friction coefficients. The results show a great influence on the friction coefficient measurements. In addition, Puls et al. developed a temperature dependent friction model in a FE model, but the simulation results were below the experimental data [2]. Rech et al. developed a pin-on-ring tribometer to ensure relevant sliding speeds and contact pressure. It could be shown, that the sliding speed between tool and chip has an impact on the resulting friction coefficients. In a final validation using FEM Simulation Rech et al. used a linear friction model dependent on the sliding speed. The results showed good agreement to the measured values [3]. In contrary to the present methods Childs used an friction model based on the local plastic strain rate to overcome the problem of proportionality of friction stresses with normal stresses influencing the chip formation and chip shape and consequently the temperature. Childs friction model showed better agreement in simulations to experimental measurements [4].

So far, no friction model was introduced including the effects of sliding speed, temperature and normal force at the same time. The aim of this paper is to analyze each listed effect on the temperature distribution separately.

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2. General Approach

The following sections will introduce the experimental friction testing set up and the modelling approach to include different friction models and a detailed phase transformation model into a 2D chip formation simulation for the material AISI 4140 (42CrMo4).

2.1. Turning experiments

The turning experiments are done on a vertical lathe from INDEX of the type V100. To realize almost orthogonal cutting conditions like in the 2D simulation, special grooved bars are manufactured, Fig.1. This workpiece has a length of 100 mm and an outer diameter of 70 mm. The width of the bars are 1.5 mm and the groove depth is 2 mm. A small EDM drilling hole is bored into the orthogonal placed cutting insert to measure the temperature on the chip using a two-color pyrometer of the type FIRE II. For more detailed information see [5] and for the insert specification Table 1.

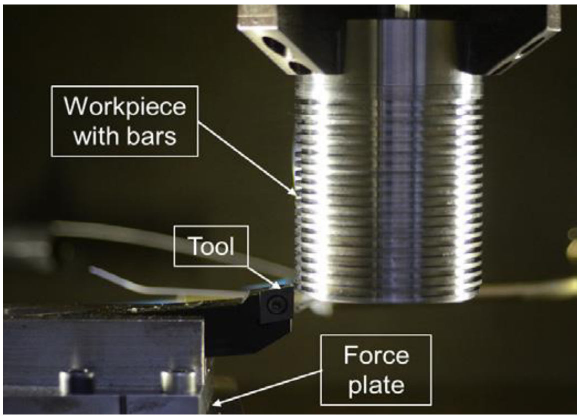

Fig.1. Experimental turning set [5]

Table 1. Tool parameters [5]

Parameters of the cutting insert	Values
Rake angle	5°
Clearance angle	2°
Radius of the cutting edge	30 µm
Cutting depth	50 µm

2.2. Friction tests

The aim of the performed friction tests is to provide experimental input data for the development of friction models dependent on the sliding speed v_s, temperature T and normal force F_N. Therefore, a laboratory tribometer of the type CETR UMT 3 (insert-on-disc) was used under dry conditions at room temperature, Fig. 2. In contrast to conventional tribometers using ball-on-disk tests to measure the friction coefficient μ, this work uses uncoated cutting inserts on a rotating disc of the material AISI 4140, to be as close as possible to the contact geometry in the turning experiments.

For the friction tests on the laboratory tribometer three different normal forces are used (10, 20 and 40 N). The sliding speed is varied from 0.2 up to 10 m/s and the temperature is measured with a thermocouple at a distance of 0.1 mm from the cutting zone. Every friction test is repeated 100 times with a new cutting insert and includes the following three step load cycle strategy. Within the first step the disc is accelerated from 0 up to 10 m/s (variable according to the measured sliding speed) within 5 s. During the next step the maximum speed is held for 5 s and is finally decreased again to 0 m/s in the last step. Only the load cycles 21 to 100 will be used for the friction models, to provide same cutting conditions for all measurements.

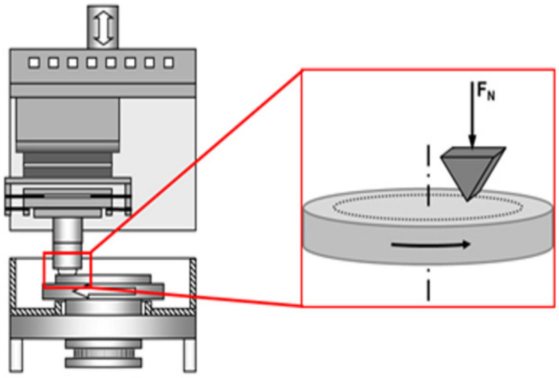

Fig.2. Laboratory tribometer of the type CETR UMTR 3 [6]

2.3. Development of the 2D simulation model

The used 2D chip formation model was developed in the commercial software ABAQUS/ standard from [5] and includes a remeshing algorithm developed and validated by [7]. The material model uses an approach from Voce and a material plastic flow criterion from von Mises to calculated the yield stress, based on the presented work from [8]. This remeshing routine and the user defined material model are necessary to define the failure of the material and the separation criterion for the chip. No information is lost during this process, like it would happen in an approach using element deleting to provide the material failure. The developed model is based on the work of [9]. The prediction of forces, residual stresses (in the surface layer) and temperatures are in a very good agreement compared to experimental results.

According to the remeshing routine the simulation is based on a Lagrangian formulation for the movement of the workpiece and the tool. The tool is modelled as a rigid body and is fixed in all directions. Only the workpiece can move in x-direction towards the tool, but is fixed in y-direction at the underside of the workpiece. For the rest of the workpiece displacement is allowed in the direction of x and y to provide the stock removal process.

Heat radiation is considered as surface boundary condition using the Abaqus subroutine SFILM on every surface being not in contact with the tool, Fig. 3. The contact between the chip and the tool transfers heat with respect to the temperature dependent heat capacities and conductivities.

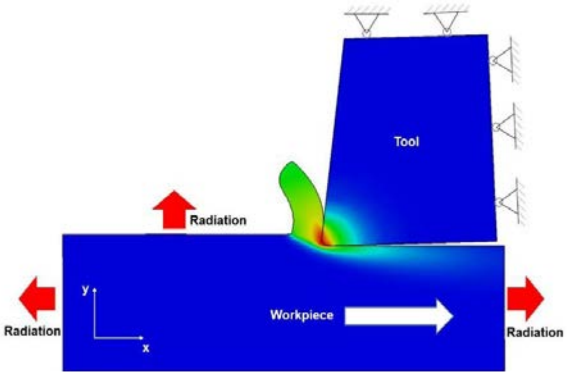

Fig.3. Lagrangian 2D chip formation model

2.4. Friction modelling

Targeting on the effect of friction coefficients on the temperature distribution and phase transformations in the surface layer the parameters sliding speed, temperature and normal force will be investigated. Therefore, 8 different friction coefficient models are comparedThe first model will just use a constant friction coefficient of μ = 0.35. As a first extension, μ will be taken into account as a function of the temperature $\mu(T)$, the sliding speed $\mu(v_S)$ and the normal force $\mu(F_N)$ to investigate the isolated influence on the temperature. In addition, all the dependencies will be paired ($\mu(F_N, T)$, $\mu(F_N, v_S)$, $\mu(T, v_S)$) and last combined into a friction model including the temperature, sliding speed and normal force $\mu(F_N, T, v_S)$. With this approach, all friction coefficient combinations will be tested in the simulation and compared to experimental results. In addition, a matching to a constant friction coefficient model will show the influence of all tested parameters.

For the implementation of these models, the strategy from Fig. 4 is used. Over the contact length chip-tool, every node in contact is checked for its temperature, sliding speed and force. Every node will be assigned to an interpolated μ according to the measured friction coefficients. For the friction models neglecting one or two parameters an average value is extracted from the μ= 0.35 simulation and used for these parameters. This becomes necessary to reduce the 3D friction coefficient plot from Fig. 4. into a 2D plot to make it usable for the isolated or paired parameter models. Consequently, the function $\mu(T)$ is $\mu(T, \overline{F_N}, \overline{v_S})$ with an average force $\overline{F_N}$ and average sliding speed $\overline{v_S}$ extracted from the simulation.

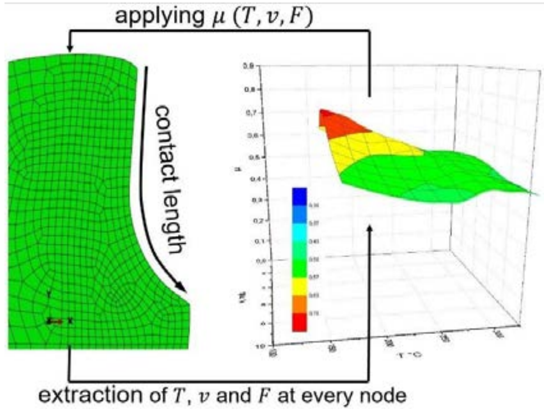

Fig.4. Method to apply the measured friction coefficients into the FEM simulation model [10]

3. Results

3.1. Friction tests

In total 4 different kinds of test variations were performed on the laboratory tribometer to measure friction coefficients in dependence of the sliding speed, temperature, force and contact geometry. The first two variations aimed on the comparison between disk-on-ball tests and tool-on-disk tests at a normal force F_N of 20 N. The results show a markedly effect from sliding velocity on the friction coefficients for the ball-on-disk, Fig. 5. Within the test from 0 to 10 m/s the friction coefficient falls down from 0.63 to 0.32 which is nearly 50% of the starting value. In contrast to the sliding speed does a temperature variation only marginally influences the friction coefficient. Closely it can be mentioned, that higher sliding speeds and temperatures lead to a lower friction coefficient.

Changing the ball to a tool modifies the contact geometry to a more realistic cutting set up for the friction measurements. This simple replacement changes the friction level drastically. All measured friction coefficients are significantly higher than in the ball-on-disk test. The highest friction coefficient is now up to 0.765 and the lowest 0.48. Furthermore, the main influence on the friction coefficient swaps from the higher sliding speed dependency in the ball-on-disk tests to a higher temperature dependency in the tool-on-disk tests, which can be seen in Fig. 6. Like in the ball-on-disk tests higher sliding speeds and temperatures lower the friction coefficient.

Increasing the normal force from 20 N to 40 N is only little affecting the overall friction level, Fig. 7. However, this increase moves the measured friction coefficient field to higher temperatures and shows a slightly higher influence on the friction coefficient by the temperature between 220 °C and 300 °C. In return leads a reduction of the normal force up to 10 N to a shift to lower temperatures for the global friction coefficient field.

The measured friction coefficients are clearly affected by all varied parameters. This fact demands on detailed modelling of friction behavior in cutting simulation, especially for lower sliding speeds and temperatures up to at least 350°C. Changes in the normal force only little influences the friction coefficients, but move the global friction coefficient level to lower temperatures. The results also offer the hypothesis that the assumption of a constant friction value between 0.35 and 0.45, which is often used in cutting simulations, is a permissible approximation for cutting processes with high sliding speeds and temperatures, because of the small changes in the friction coefficient at these cutting conditions of more than 6000 mm/s.. But the results also show a lack of predictiveness for friction coefficients at high temperatures. For all test set ups the maximum temperature never exceeded 463°C what makes this test mechanism only valid for lower to medium temperature fields. The measurement of friction coefficients for high temperatures demand a change in the measurement method like for example a broaching machine. Consequently, an extrapolation of the friction coefficients for higher temperatures in the FEM-simulation based on the measurements becomes essential but may falsify the simulation results. However, the failure is expected to be of less impact, because of only small change in the friction coefficient gradient at the highest measured temperatures.

3.2. Simulation using different friction models

The friction models described in 2.4 were implemented in a 2D chip formation simulation and investigated for their predictive capability to calculate temperatures in the surface of the workpiece. For the simulation set up the cutting speeds 100-300 m/min were taken into account.

Fig. 8. shows the comparison of the different friction models at a cutting speed of 100 m/min. The friction model using a constant value of μ = 0.35 reaches the lowest temperature after a cutting distance of 1 mm. The highest temperature is reached for the combined model of $\mu(F_N, T, v_S)$ and is about 50 °K higher than for the constant friction value of μ = 0.35. Taking a look at the friction coefficient models with only one varying parameter, $\mu(F_N$) shows the greatest influence on the temperature of all isolated models. The model $\mu(v_S)$ even starts at lower temperatures like the μ = 0.35 model and does not reach higher temperatures before a cutting distance of 750 µm. The temperature dependent model $\mu(T)$ increases in temperature much faster than the constant model for the first 300 µm. At a cutting distance of 400 µm both models show nearly the same gradient. Nearly the same trend like the $\mu(T)$ can be seen for the pressure dependent model $\mu(F_N)$. This model reaches only about 10 °K higher temperatures than the $\mu(T)$ model at the cutting distance of 1 µm. The paired models $\mu(F_N, T)$ and $\mu(T, v_S)$ reach higher temperatures and have a higher gradient at short cutting distances compared to the constant model but don't show great differences to the isolated models $\mu(T)$ and $\mu(F_N)$. Only the paired model $\mu(F_N, v_S)$ increases longer in the maximum temperature and reaches the same temperatures as the combined friction model (F_N, T, v_S) after 750 µm. The temperature curves for the cutting speed 200 m/min mostly show similar trends, Fig. 9. Once more the highest temperature gradient at the beginning and highest temperatures at the end of the simulation are reached for the $\mu(F_N, T, v_S)$ model.

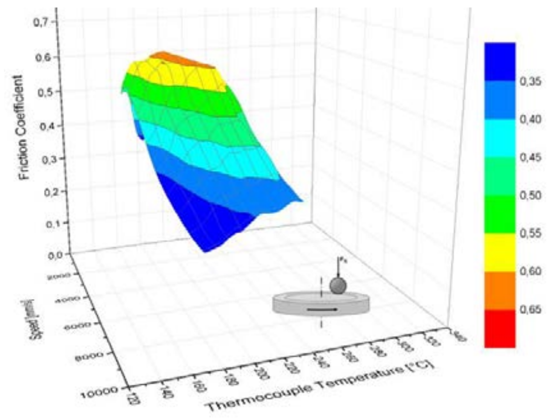

Fig. 5.Friction measurements using ball-on-disk tests at 20 N

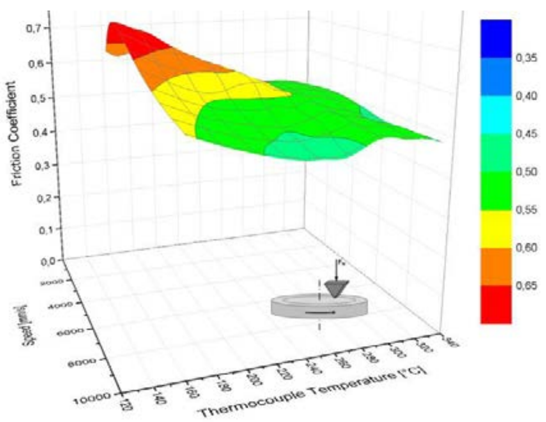

Fig. 6. Friction measurements using tool-on-disk test at 20 N [6]

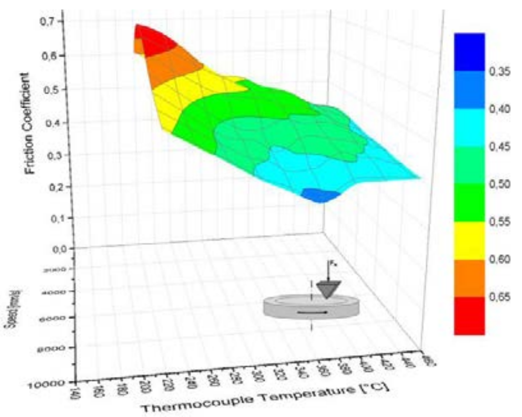

Fig. 7. Friction measurements using tool-on-disk test at 40 N [6]

The constant value model μ = 0.35 reaches again not the high temperatures like all other models, except the curve from model $\mu(T)$. In consequence both paired friction coefficient models including a temperature dependency $\mu(F_N, T)$ and $\mu(T, v_S)$ are below the curves of the isolated models using the normal force $\mu(F_N)$ and sliding speed $\mu(v_S)$ dependency. An explanation may be found in the measured friction coefficients where a high decline of the friction coefficient appears for increasing temperatures. Like for the lower cutting speed the paired friction model $\mu(F_N, v_S)$ achieves about the same cutting temperatures at a cutting distance of 1 mm like the combined model $\mu(F_N, T, v_S)$. It has to be mentioned that the temperature difference increases up to 60 K.

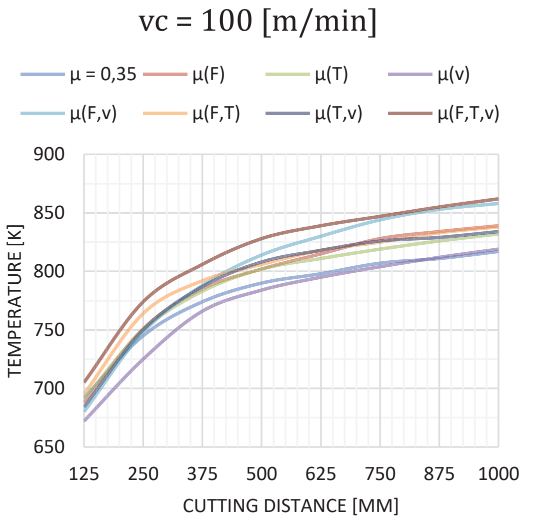

Fig. 8. Comparison of the different friction coefficient models at a cutting speed of 100 m/min

For the highest cutting speed only the constant model and the combined model were taking into account, Fig. 10. Like shown for the lower cutting speeds the combined model is again clearly above the constant model. Fig. 11 shows comparison of the reached max. temperatures between the constant model, combined model and experimental results.

A deeper look at the comparison between simulation and experimental turning experiments shows a better agreement of the combined friction model $\mu(F_N, T, v_S)$ than the model using only a constant value of μ = 0.35, see Fig. 10. For the cutting speed 100 m/min the relative discrepancy of the constant model to the experimental measurements is 7.6 % and for the $\mu(F_N, T, v_S)$ 3.3 %. This divergence increases for the cutting speed of 200 m/min. The relative deviation reaches 7.5 % for the μ = 0.35 and 4.4 % for the $\mu(F_N, T, v_S)$ model. The highest cutting speed has a deviation of 7.2 % for the constant model and 3.9 % for the combined model.

Taking a look at the chip formation within the eight different simulation models it can be seen, that the chip shape differs due to the changed thermo-mechanical load caused by the friction coefficient models. In Fig. 12 five exemplary chip shapes are presented. This shape deviation is based on changes in the shear plane.

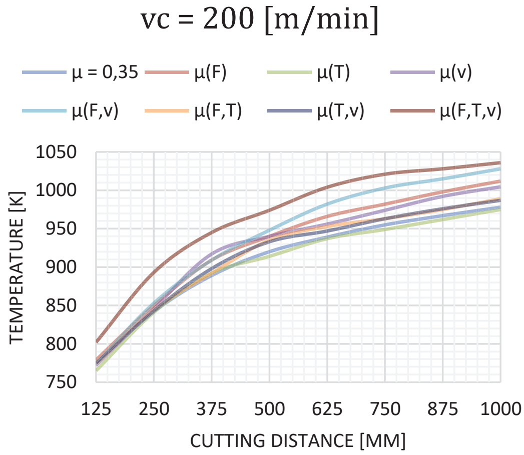

Fig. Comparison 9. of the different friction coefficient models at a cutting speed of 200 m/min

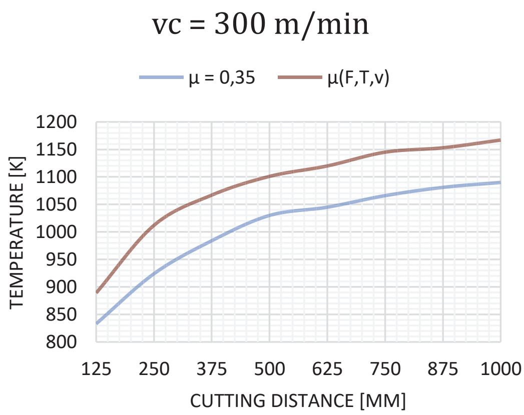

Fig. 10. Comparison of the different friction coefficient models at a cutting speed of 300 m/min

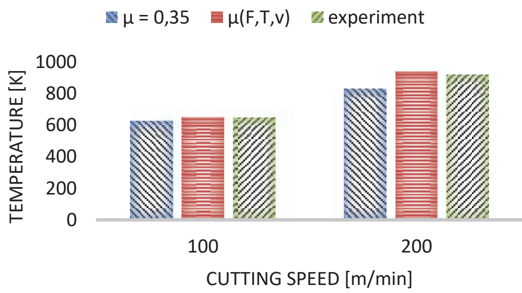

Fig. 11. Comparison between the friction models μ = 0.35, $\mu(F_N, T, v_S)$ and experimental turning results based on Michna [11]

As a result $\mu(F_N)$, $\mu(T)$ and $\mu(v_S)$ show totally different chip shapes compared to the constant or the combined model. For the $\mu(v_S)$ model the chip even sticks on the cutting tool. This behavior only changes after reaching nearly the complete simulation distance of 1 mm.

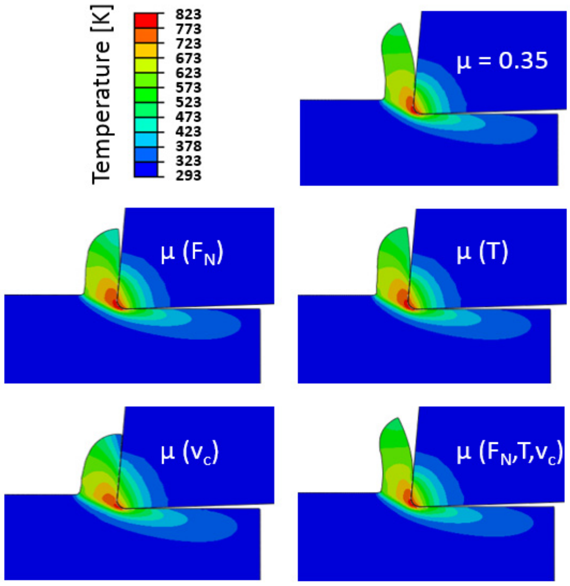

Fig12. Influence of the chip shape from different friction coefficient models, at a cutting speed of 100 m/min

4. Summary and Conclusion

Within this work a laboratory tribometer was used to measure friction coefficients dependent on the sliding speed, temperature and normal force. Therefore, two different contact geometries represented by a ball and an insert were used. The temperature was measured using a thermocouple within the ball and the insert. Based on the experimental results 8 different friction coefficient models were developed and implemented in a 2D chip formation simulation within the software Abaqus/Standard. These models differ in their parameter dependency using a constant friction coefficient, isolated modelling of the temperature, force and sliding speed as well as paired models and a combined model using all parameters. The results show a big difference in the rising cutting temperatures. The constant friction model using only $\mu = 0.35$ mostly reaches the lowest maximum temperatures and the combined model using the dependency of $\mu(F_N, T, v_S)$ has the highest temperatures. A comparison between the constant and combined model with experimental turning results shows better agreement for the combined model. The best agreement showed the paired model $\mu(F_N, v_S)$. All models showed small changes in the chip shape what makes it probably necessary to take the effect of the plastic strain rate in the shear zone into account [4]. For the prediction of phase transformations, it becomes essential to use an adequate friction coefficient model, because the calculated temperatures differ significantly between the 8 models. So the amount of transformed austenite and the starting point of the martensite transformation could be highly be affected by the friction model.

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References

[1] Arrazola PJ, Ugarte D, Dominguez X. A new approach for the friction identificcation during machining through the use of finite element modeling. Int. J. Mach Tool & Manu, Volume 48 (2008), pp. 173-183.
[2] Puls H, Klocke F, Lung, D. Experimenteal investigation on friction under metal cutting conditions. Wear, Volume 310, Issue 1-2 (2014), pp. 63-71.
[3] Rech j, Claudin C, D'Eramo E. Identification of a friction model – Application to the context of dry cutting of an AISI 1045 annealed seel with a TiN-coated carbide tool. Tribology International, Volume 42, Issue 5 (2009), pp. 738-744.
[4] Childs THC. Friction modelling in metal cutting. Wear, Volume 260, Issue 3 (2006), pp. 310-318.
[5] Schulze V, Michna J, Schneider J, Gumbsch P. Modelling of cutting induced surface phase transformations considering friction effects. Procedia Engineering, Volume 29 (2011), pp. 331-336.
[6] Bollig P, Michna J, Faltin C, Schneider J, Zanger F, Schießl R, Maas U, Schulze V. Experimental and simulative modeling od drilling processes for the compensation of thermal effects. Lecture Notes in Production Engineering (2017). Submitted
[7] Schulze V, Zanger F. Development of a simulation model to invetigate tool wear in Ti-6Al-4V alloy machining. Adv. Mat. Res., Volume 223 (2011), pp. 535-544.
[8] Autenrieth H. Numerische Analyse der Mikrozerspanung am Beispiel von normalisiertem C45E, Dissertation Universität Karlsruhe (TH), 2010.
[9] Schulze V, Autenrieth H, Deuchert M, Weule H. Investigation of surface near residual stress states after micro-cutting by finite element simulation, CIRP Annals – Manu. Techn., Volume 59, Issue 1 (2010), pp. 117-120.
[10] Schulze V, Michna J, Zanger F, Faltin C, Maas U, Schneider J. Influence of cutting parameters, tool coatings and friction on the process heat in cutting processes and phase transformations in workpiece surface layers. J. Heat Treatm. Mat., Volume 68 (2013), pp. 22-31
[11] Michna J. Numerische und experimentelle Untersuchung zerspanungsbedingter Gefügeumwandlungen und Modellierung des thermo-mechanischen Lastkollektivs beim Bohren von 42CrMo4, Dissertation, Karlsruher Institute für Technologie, 2014.