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*FEM, constitutive models,
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SENSITIVITY ANALYSIS OF THE CONSTITUTIVE MODELS IN FEM-BASED SIMULATION OF THE CUTTING PROCESS

The paper considers the problem of the influence of constitutive model parameters on the results of FEM-based simulation of the orthogonal cutting process using C45 (AISI 1045) carbon steel and multilayer-coated carbide tool. The simulations were based on the power constitutive law (PL) with a special consideration of the temperature-related thermal influences. The sensitivity analysis performed concerns the models proposed by Özel and Kalhori and own data in the form of multi-regressive equations for the substrate and coating components that were applied. In particular, the values of n exponent were varied in order to assess the simulation results. The FEM simulations include the average interface temperature, the distribution of temperature on the rake face and within the wedge body, as well as cutting forces. By modifying the PL parameters, the prediction errors lower than 15% were obtained.

1. CONSTITUTIVE MATERIAL MODELS IN FEM SIMULATION

Modelling of machining processes in terms of multi-criteria optimization is currently developed in order to support the implementation of new technological chains into the production. For this reason the FEM based simulation is a basic engineering tool in modern industry. Unfortunately, all popular FEM simulation methods, i.e. Lagrangian, Eulerian, Arbitrary Lagrangian Eulerian (ALE) methods are not able to include into the cutting model all corresponding physical phenomena with acceptable engineering accuracy [1],[2],[3].

According to the current knowledge of metal cutting the threshold is the development of more accurate and complete constitutive material models which consider the appropriate mechanical thermophysical properties of both workpiece and tool materials [4-7].

The success in developing the constitutive models depends on solving three important problems:

- Definition of mechanical properties of the workpiece material under cutting conditions,
- Specification of the thermophysical properties of the workpiece and cutting tool materials including thin layered coatings [5],[8],
- Quantification of friction in the cutting zone [7],[9],[10].

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It should be underlined that the FEM is one of the leading machining problems and is very popular among metal cutting experts and scientists. Moreover, the FEM constitutive model should meet the High Speed Cutting (HSC) and High Performance Cutting (HPC) demands and can be validated for a wide range of machining parameters, especially the cutting speed [11],[12]. In addition, it should cover a wide spectrum of cutting tool materials including multilayer coated and composite tools.

Bearing in mind all these modelling aspects and barriers, in this study the focus is made on the influence of model parameters for prediction accuracy under orthogonal cutting conditions. The second important consideration is the influence of temperature on the strain-stress diagram.

2. METHODOLOGY OF INVESTIGATIONS

In this paper the modified Lagrangian equation was used to predict the thermal and mechanical effects occurring during orthogonal cutting process of the C45 steel. The tool material was WC-6%Co sintered carbide coated with three-layer $TiC/Al_2O_3/TiN$ (3L) coating. The sensitivity analysis includes two constitutive material models used in AdvantEdge commercial package [13], i.e. standard and PL-TD (*Power Law – Temperature Dependent*). In addition, the PL-TD model was completed using two sets of model parameters specified in Table 1.

In order to validate the FEM predictions, F_c and F_f cutting forces were measured under free and non free orthogonal cutting conditions. In the first case a strain–gauge dynamometer with a SNAP Master data acquisition system was applied. In the second case, the forces in semi-orthogonal cutting were measured using Kistler 9257B piezoelectric dynamometer equipped with 5019B amplifier and NI 6062E, National Instruments, A/D multi-channel board. The visualization of the recorded force signals and its processing was performed using CutPro data acquisition system.

As mentioned earlier, the FEM modelling utilizes standard and PL-TD constitutive models, which mathematically are expressed by the same power equation, as follows

$$\sigma_f\left(\varepsilon_p\right)=\sigma_o\Theta(T)\left(1+\frac{\varepsilon_p}{\varepsilon_p^0}\right)^{1/n} \tag{1}$$

where: σ_o is the initial yield stress, ε_p is the plastic strain, ε_p^0 is the reference plastic strain, *1/n* is the strain hardening exponent and $\Theta(T)$ is thermal softening index defined as a function of temperature according to (2).

In equation (2) the c_0 through c_5 are coefficients for the polynomial fit, T is the temperature, T_{cut} is the linear cut off temperature, and T_{melt} is the melting temperature. The equation (2a) is defined for $T<T_{cut}$, where equation (2b) for $T\geq T_{cut}$.

$$\Theta(T)=c_0+c_1T+c_2T^2+c_3T^3+c_4T^4+c_5T^5 \tag{2a}$$

$$\Theta(T) = \Theta(T_{cut})\left(1 - \frac{T - T_{cut}}{T_{melt} - T_{cut}}\right) \tag{2b}$$

It is important for the researcher that it can define own model parameters in the PL-TD constitutive model, using literature data or experimental results. It should be noted that the FEM model ignores the thermal softening effect of the cutting tool material. In this study these data were kept the same as in Ref. [8]. The influence of thermophysical properties of the machined C45 steel on the FEM predictions was tested for three groups of relevant data given by Kalhori [14], Özel and Karpat [10], and available in AdvantEdge (AE) package [13]. The thermophysical properties of the machined C45 steel were selected based on own investigations [8] and own database MPDB [15]. In particular, they include temperature-based thermal conductivity, specific heat and thermal expansion (linear expansion coefficient α), which were kept constant for all material models considered in this comparative study. All the above mentioned data are verified in Figs. 1 and 2.

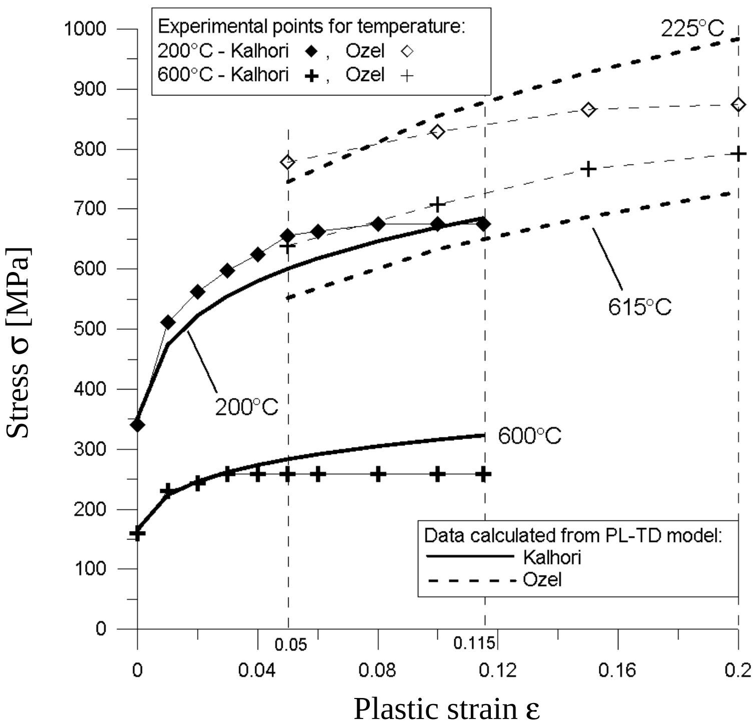

Fig. 1. Stress-strain function determined by eq. (1) for a set of experimental data

It is evident in Fig. 1 that the Kalhori's analysis assumes substantially lower values of stress (doted lines) than those determined by Özel and Karpat [10]. On the other hand, the function $\sigma(\varepsilon)$ in the Kalhori's model [14] was obtained for the temperature range of 20°C - 800°C and plastic strain varying from 0 to 0,115.

On the other hand, Özel and Karpat consider the temperature range of 60°C-625°C and plastic strain of 0,05-0,2 respectively. Computed values of parameters of the power constitutive model given by eq. (1) are specified in Table 1.

Table 1. Constitutive model parameters - equations (1) and (2) - calculated for the C45 carbon steel according to the data by Kalhori [14] and Ozel and Karpat [10]

Parameters	Kalhori	Özel and Karpat
c_0	1,0018	1,0162
c_1	$-3{,}57\ 10^{-4}$	$-7{,}60\ 10^{-5}$
c_2	$-1{,}39\ 10^{-6}$	$-1{,}20\ 10^{-6}$
c_3	$5{,}95\ 10^{-10}$	$8{,}00\ 10^{-10}$
c_4, c_5	0	0
σ_o, Pa	$401\ 10^6$	
ε_p^0	0,00191	
n	6,2	4,9
T_{cut}, ^oC	800	625
ε_{cut}	0,115	0,200
Error, %	11	7

In this analysis, the values of the yield stress and the reference plastic strain were assumed to be constant and equal to σ_o = 401MPa and ε_p^0 = 0,00191 respectively.

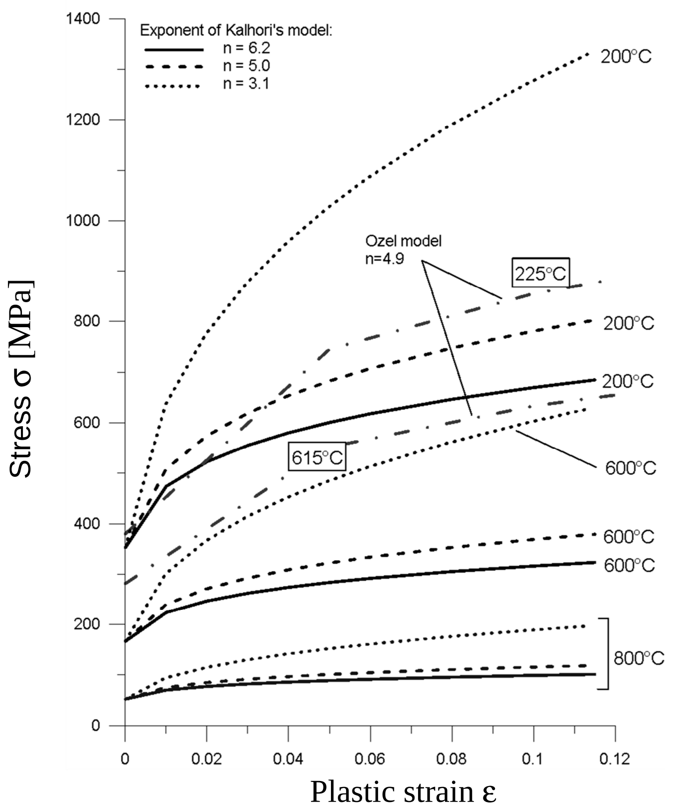

Fig. 2. Stress - strain curves for the constitutive power model (1) using Özel's data and Kalhori's data with variable n values (n=6,2 – experimental, n=5,0 and n=3,1 – modified models)

As a result, the relative errors determined for data provided by both reference models were about 11% and 7% respectively. As mentioned earlier, variations of the *n* exponent in the constitutive power law (1) can substantially influence the $\sigma(\varepsilon)$ function. Fig. 2 illustrates how the $\sigma(\varepsilon)$ function changes when *n* is equal to 3,1, 5,0 and 6,2, respectively. As can be noted in Fig. 2, the constitutive Power Law (CPL) model is less sensitive to the *n* variations when the temperature increases. Changes of the thermal softening (TS) index, expressed by term $\Theta(T)$ in eq. (1) are shown in Fig. 3.

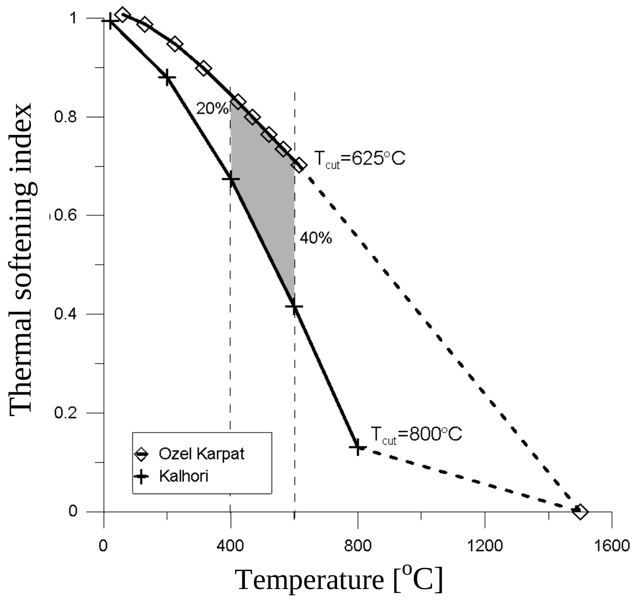

Fig. 3. Thermal softening of C45 steel calculated by eq. (2) for the data given in Table 1

In Fig. 3 values of TS index vary from 1, which is related to the ambient of 20°C, to 0, which corresponds to the melting temperature. In this computation algorithm, the thermal softening function was assumed to be linear in the temperature range from that defined by own experiments up to the melting point. It should be emphasized that material plasticizing due to the thermal softening occurs faster when Kalhori's model is used (20% and 40% at 400°C and 600°C respectively in relation to the Özel's data). It is evident that for the same values of strain and yield stress, the calculated values of the stresses are lower than those determined by Özel's model. In addition, this effect will be more pronounced by higher values of the strain-hardening exponent *n*.

As a result of model modifications, some important relationships were observed during comparisons of *n* effects on the thermal behavior of the workpiece material. For low temperatures of about 200°C, comparable stress values are obtained for comparable values of *n* exponent, i.e. *n*=5,0 for Kalhori's model and *n*=4,9 for Özel's model, as shown in Fig. 2. When temperature increases the experimental data coincides well with the Kalhori's model assuming *n*=3,1. This fact can be explained by a different approach for modelling of the thermal softening effect because, as shown in Fig. 3, the model by Özel is less sensitive to the temperature increase. In fact, in the temperature range of 400-600°C, the average thermal softening index determined by Özel is 20-40% less than for Kalhori's data. It should be noted that in the Kalhori's approach, the stress-strain function $\sigma(\varepsilon)$ was determined without modification of $\Theta(T)$ term. Such an approach allows an explicit determination of the influence of *n* exponent on the FEM predictions in the AE system.

3. EXPERIMENTAL RESULTS

3.1. THERMAL EFFECTS

The analysis of the experimental results was performed in two stages. The first part was focused on the variations of the cutting temperature resulting from variations of the thermophysical properties in the FEM model. The second stage concerns the assessment of the influences of the mechanical properties including changes of the cutting forces and the distributions of the reduced stresses on the tool rake face.

Fig. 4 shows the average values of the cutting temperature determined by FEM simulations taking into account four different material models. The first finding is that the predicted cutting temperatures based on the data collected in AE database were distinctly higher than measurements. This specifically concerns the AE PL-TD model in which the thermophysical properties of the tool material depend on the temperature [8]. In this case the workpiece material model is the same as the AE Standard model. It is concluded that measured temperatures fit well the simulated results using input data by Kalhori [14], taking into consideration relatively large variations of the experimental results.

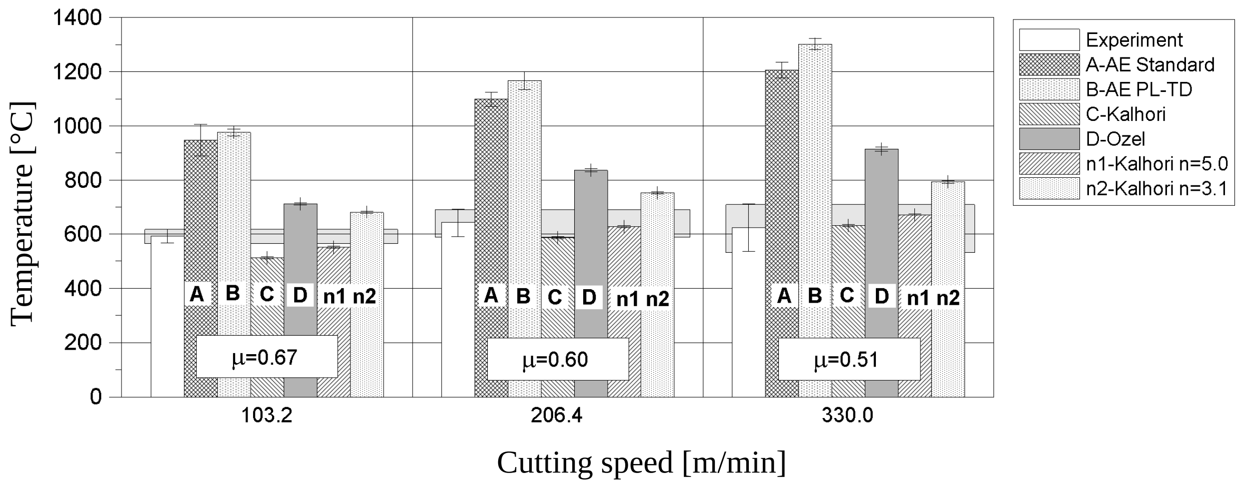

Fig. 4. Comparison of the measured temperatures with FEM predictions (original and modified). Confidence interval P = 95%

As shown in Fig. 4, a small decrease of *n* exponent down to 5,0 causes that the temperature increases slightly of about 5% (comparison of cases C and n1). This trend coincides with stress-strain model shown in Fig. 2 for which stress increases when *n* decreases from the reference value *n*=6,2 to 5,0.

The fact that for the temperature of about 600°C the $\sigma(\varepsilon)$ curves fit each other well (*n*=3,1), can result in comparable FEM temperature predictions. In fact, the average interface temperature obtained by means of FEM reference model was also about 600°C. Unfortunately, this hypothesis was not confirmed by simulation results. For instance, the reduction on *n* exponent by a half, i.e. to *n*=3,1 caused that the temperature increased and instead of comparable stress values for both Özel's and Kalhori's models the predicted temperatures are different (bars D and n2). The simulations were carried out using the same thermal properties for the work and cutting tool materials. It seems that the decisive factor which controls the interface temperature is thermal softening illustrated in Fig. 3.

Fig.5 shows that the variant of the constitutive model of workpiece material does not markedly change the temperature distribution on the rake face. Due to this evidence, the maximum interface temperature is localized at a constant distance of about 0,22mm from the cutting edge. Moreover, the characteristic "*plateau*" effect is visible for material models by Kalhori and Özel. On the other hand, the application of the temperature-dependent thermophysical properties of the cutting tool material causes that the temperature decreases monotonically starting from the vicinity of the cutting edge. This effect can confirm an important influence of changes of the thermal conductivity and specific heat on the distribution of isotherms on the tool rake face.

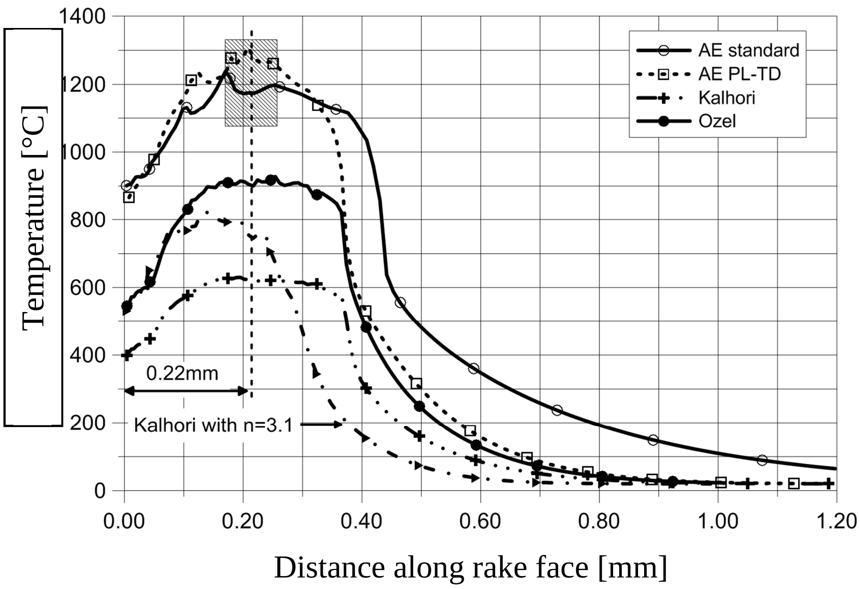

Fig. 5. Temperature distribution along the rake face vs. analyzed FEM simulation models. Cutting speed of v_c=330m/min

The role of the constitutive model type in thermal simulations can be assessed from Fig. 6 which shows the temperature distribution beneath the rake face inside the tool body. In the case of the Power Law Temperature Dependent (PL-TD) model, in which thermal properties of both matted materials are dependent on temperature, the isotherms are parallel to each other at a certain distance between them. For these kinds of FEM models the temperature gradient inside the coating and the substrate is equal to 3-10°C/μm and 2-6°C/μm respectively.

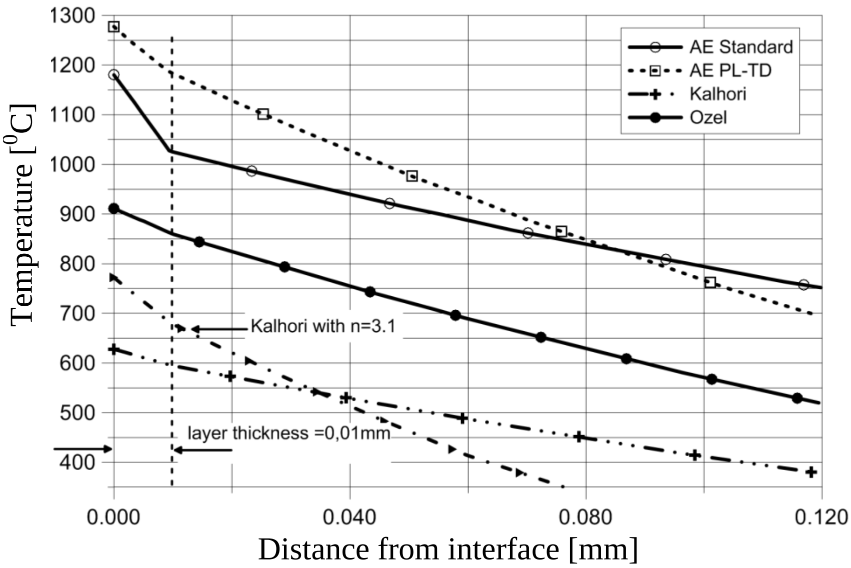

Fig. 6. Temperature distribution below the rake face at the point of maximum contact temperature for 3L coated tools and all analyzed FEM simulation models. Cutting speed v_c=330m/min

The minimum variations of the temperature gradients are obtained for Kalhori's model, for which also minimum average interface temperatures were predicted. The standard model gives distinctly higher temperature gradients of 15°C/μm for the coating but lower ones of 2°C/μm for the substrate. The reason is that for the average cutting temperatures of about 900°C also the influence of temperature on the material properties can be a decisive factor. Moreover, it can be noted for both models that the multilayer coating including TiC, Al_2O_3 and TiN layer of 1μm, 6μm of 3μm in thickness plays a role of the thermal barrier and restrains the heat transfer into the tool substrate. Similar temperature distributions were obtained for cutting speeds of 103 and 206m/min.

No visible effects on the temperature distribution along the rake face and inside the tool body resulting from the *n* variations were obtained.

3.2. MECHANICAL EFFECTS

The values of force components are compared in terms of FEM model types in Fig. 7. It is reasoned that this factor plays an important role in the simulation of the decohesion of the workpiece material.

The observed differences relate not only to the values of the cutting forces but also the courses of both components F_c and F_f. In general, higher values of cutting force were obtained for the standard FE model which utilizes the input data from the AE database. The minimum values of both components resulted from the Kalhori's model, as indicated by bar #C in Fig. 7. This constitutive material model gives low stress values in the entire range of strains and temperatures.

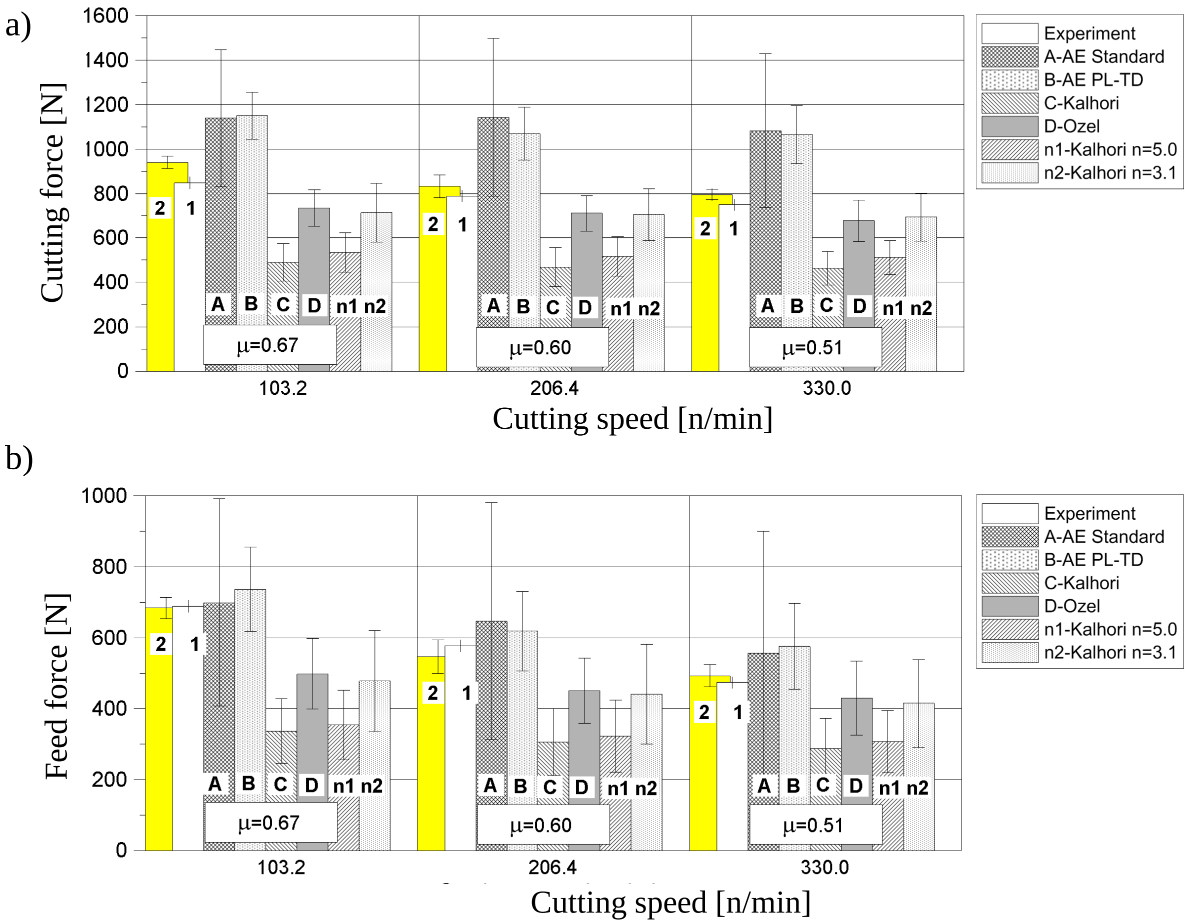

Fig. 7. Summary of the experimental values of the: cutting force (a), feed force (b), with FEM simulation data (original and modified) taking into account confidence interval of P = 95%. Numbers 1 and 2 describe the values of experimental data obtained in orthogonal and semi-orthogonal turning processes respectively

A good agreement was achieved when using Özel's model. In this case, the differences between measurements and predictions do not exceed 10% for the whole range of cutting speeds. On the other hand, it was revealed that the feed force predictions are very sensitive to the cutting speed. The prediction accuracy increases from 30% to 10% when cutting speed increases.

It should be noted that despite different measuring devices and different machining conditions (free orthogonal vs. non-free cutting) the measured values of the cutting force F_c and feed force F_f differ slightly from each other (Fig. 7 – bars # 1 and 2). The standard deviations of the dynamic measuring signals are in the range of ±50N and ±10N for piezoelectric and strain-gauge dynamometers respectively. These data are very important in terms of the acceptability and the accuracy of FEM simulation and the constitutive models used.

A relatively good agreement between forces predicted by Özel's and Kalhori's model with n=3,1 can suggest that for comparable $\sigma(\varepsilon)$ functions also the predicted cutting forces will be of comparable values (see bars D and n2 in Fig. 7). It is obviously known the stress-strain relationship controls the decohesion process and the simulations of mechanical characteristics give such an effect, despite the different values of parameters in the constitutive models.

Fig. 7 shows that simulation models result in higher variations of the values of the cutting force. For instance, for FEM simulations which utilize PL-TD model, the standard deviation of the cutting force signal is about ±100N regardless of the simulation variant used. In contrast, the standard FEM model gives very high scatters, especially for the feed force F_f (±300N). This fact can be explained by the poor identification of the thermal properties at high cutting temperature including the occurrence distinct material plasticizing.

4. SUMMARY

Based on the experimental results and FEM predictions the conclusions are as follows:

- Popular constitutive models cannot be universal in terms of both mechanical and thermal characteristics due to the different approach for modelling of the stress-strain relationship and thermal softening effect.
- The n exponent influences the FEM predictions but its importance depends on the individual thermophysical characteristics of the materials. Such a sensitive analysis can support the selection of optimum mechanical characteristics of the cutting process.
- The thermal softening index can also be used to predict optimum thermal characteristics of the cutting process.
- The predicted cutting forces and the average cutting temperature as well the distribution of isotherms on the rake face differ substantially when the thermophysical properties (λ, c_p, α) in the material models are the same, but models of $\sigma_f(\varepsilon_p)$ are different.
- The best agreement between the measured and simulated forces was achieved for model parameters proposed by Özel and better fitting of the measured temperatures to the predicted values was found for the input data given by Kalhori.

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