Journal of Machine Engineering, Vol. 17, No. 3, 2017

Received: *30 January 2017* / Accepted: *10 June 2017* / Published online: *28 September 2017*

modeling, machining,
constitutive model

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MODELLING OF MATERIAL BEHAVIOUR FOR INCONEL 718 SUPERALLOY USING EXPERIMENTAL DATA

In this paper parameters of the Johnson-Cook (J-C) constitutive material model were predicted more accurately based on the static and dynamic material tests and mathematical modelling of relevant response surfaces using specially developed Matlab scripts. Experimental tests were performed under strain rates of 10^{-3} and 10^{1} 1/s and the temperature ranging from the ambient up to 700°C. As a result, a set of mathematical models which fit the experimental data was determined. The experimentally-derived constitutive models were implemented into FEM-based simulations of real machining processes of Inconel 718.

1. INTRODUCTION

Modelling of the machining process and various machining operations using FEM utilizes plastic, elastic-plastic, visco-plastic and elastic-visco-plastic material models [1]. In practice, in order to improve the accuracy of FEM predictions such associate physical effects as the strain-hardening, thermal softening as functions of three factors- strain, strain rate and temperature are considered in constitutive material models. As a result, several constitutive models which take into account these variable factors are used by FEM users [1,2,3,4]. In this comparative study, a classical Johnson-Cook model in the form of Eqn. (1) was selected but the constant *A*, *B* and *C* and exponents *m* and *n* were determined experimentally.

$$\sigma_{eq} = \left(A + B\varepsilon_p{}^n\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_p^0}\right)\right)\left(1 - \left(\frac{T - T_o}{T_t - T_o}\right)^m\right) \tag{1}$$

where: σ_{eq} - equivalent flow stress, ε_p - the equivalent strain, $\dot{\varepsilon}_p$ - the equivalent strain rate, $\dot{\varepsilon}_p^0$ - the reference strain rate, T - temperature, T_0 - ambient temperature, T_t - melting temperature, A,B,C,n,m - material constants and exponents respectively.

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The Johnson-Cook (J-C) model is the most popular material constitutive law used in FEM simulations for modelling material behaviour in the primary and secondary shear zones. Its physical limitation is that Eqn. (1) involves plastic deformation below fracture initiation (equivalently to the separation of mesh nodes). On the other hand, the material constitutive models used in machining modelling should include both material fracture in the chip formation zone and an intensive thermal effect. These two physical effects are particularly important in machining of heat resistant nickel-based alloys (typically Inconel 718) which retain high strength at a high temperature. In practice, the above-mentioned effects needs some modifications of the J-C model, including:

- thermal softening [3,4],
- thermal softening as a function of temperature,
- strain hardening for higher strain rates [5].

The constants and exponents in the J-C model for Inconel 718 (model A) selected from literature sources [6,7] and those fitted to the experimental data for the temperature values of T=20-700°C (model JC1) and T=400-700°C (model JC2) are specified in Table 1.

Table 1. Parameters of J-C model for Inconel 718 alloy

Code	A, MPa	B, MPa	n	C	m	Literature item
A	1241	622	0.652	0.0134	1.30	[6,7]
JC1	1012	393	0.125	0.0271	2.42	developed
JC2	1012	511	0.396	0.0271	4.33	developed

Based on the literature survey performed the most adequate constitutive model for Inconel 718 was derived by Uhlman *et al.* [8,9]. This model implemented into FEM- DEFORM software was found to give a good agreement using between measured and predicted values of cutting forces. An important finding of this study is that the thermal softening effect does not depend on the strain rate in the J-C model. On the other hand, the value of C parameter depends on both temperature and strain rate as in a method developed by Warnecke and Oh [10]. In particular, the maximum value of C parameter changes from 0.017 to 0.03 for the temperature range of 500 to 800°C. Based on mathematical modelling using MATLAB the authors observed that such changes of C parameter do not influence the strain hardening module in Eqn (1) because the equivalent flow stress σ_{eq} changes only in the range of several percent. As a result, they can be practically neglected.

2. DERIVATION OF J-C CONSTITUTIVE MODEL FOR INCONEL 718

2.1. DETERMINATION OF MATERIAL CONSTITUTIVE MODELS

As mentioned above this modelling procedure concerns an optimal material constitutive model for an Inconel 718 nickel-based alloy and relevant FEM simulations of both turning and milling operations performed on parts of jet engines. This goal was achieved by detailed analysis of a number of material constitutive models applicable for FEM simulations, their verification based on literature data in special applications to difficult-to-machine aerospace materials and the final choice of the best material models in order to simulate appropriately machining processes and operations.

The selection of material parameters in the J-C models takes into account the mechanical and thermal effects which influence distinctly the material behaviour during metal cutting [11]. All material data concerning nickel-based alloys machined, needed for FEM simulations, were provided by the aerospace plants in Poland. They were implemented into a special data base. The mathematical modelling of the J-C equations was performed using a MATLAB program.

2.2. EXPERIMENTAL METHODOLOGY

This experimental study was carried out using the following devices and apparatus:

1. The testing machine model INSTRON 5982 for static tensile tests performed under the test temperature of 20°C to 700°C.
2. The dilatometer model BÄHR 850 D/L in order to establish the material behaviour at a higher strain rate of $\dot{\varepsilon}_p$ = 12.5 1/s and a very high temperature of 900°C.
3. Split-Hopkinson's pressure bar device designed by Polish Technical Military Academy in Warsaw in order to determine the influence of the strain rate on the flow stress.

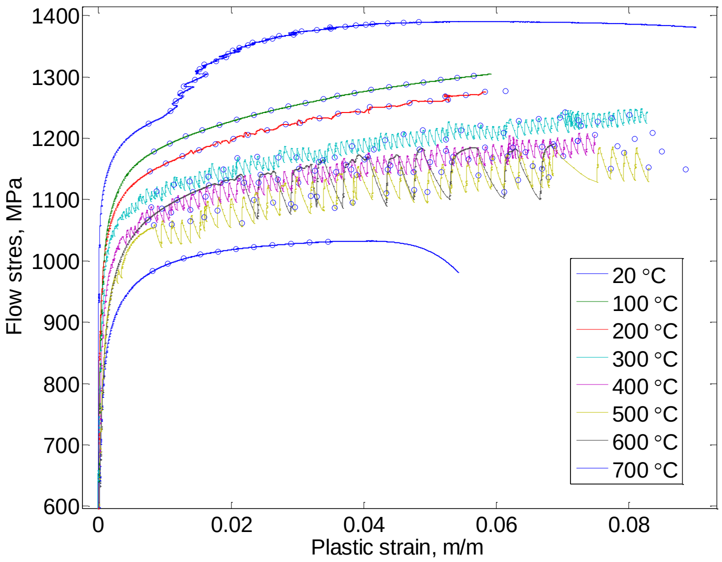

Fig. 1. Graph $\sigma = f\left(\varepsilon_p, T\right)$ for stresses above yield stress with marked approximation points

Firstly, static tensile tests were carried out in the temperature range between 20°C to 700°C. The material data obtained were analysed and converted to Matlab program by means of appropriate mathematical transformations which were made automatically using a special script. When this script was activated, the files of „*mat*" type were generated and selected in terms of the test temperatures. The data was obtained for a static tensile test performed with low strain rates limited by linear movement of the testing machine, i.e. ε_p^0 =2.604 10^{-3} 1/s. The relation $\sigma = f(\varepsilon, T)$ is related to both elastic and plastic strains but for FEM modeling elastic deformation should be omitted. Consequently, the separation of elastic and plastic strains using the experimentally determined values of Young modulus E for all ranges of the temperature was performed.

In order to determine the variable parameters in the J-C material model the matrix of points with constant variation step was defined and the experimental data were approximated to the selected constitutive model using subprogram *Sftools* available in Matlab program. An example of point arrangements for the approximation in the plastic deformation region is shown in Fig. 1.

2.3. MATHEMATICAL FITTING OF CONSTITUTIVE MODEL

The mathematical (response) function of the J-C material model expressed by Eqn. (1) was determined using *Sftool* module available in Matlab program. The J-C equation was inserted after some modifications using *Customer Equation* function. It should be noticed that in this case the model parameters are determined for the flow stresses corresponding to low strain rates. For such a case the term of Eqn. (1) with strain rate ε_p is equal to 1. Because for an Inconel 718 the melting temperature varies in the range of T_m=1250-1294°C the average melting temperature was assumed to be equal to T_m=1277°C.

As a result, the J-C constitutive material model corresponding to lower strain rates of ε_p^0 =2,604 10^{-3} 1/s) can be approximated by Eqn. (2) and fitted with the R-square of 0.6283 as follows

$$f(T,\varepsilon_p) = (1012 + 393 \cdot \varepsilon_p^{0.125}) \cdot (1 - ((T-20)/1255)^{2.42}) \tag{2}$$

Because in the cutting process the material is plastically deformed under high strain rates, the appropriate parameters in the second module of the J-C model, especially at high temperatures, should be determined using the dilatometer. Its application allows the flow stress values $\sigma = f(\varepsilon_p, T)$ for higher strain rates of ε_p = 12.5 1/s to be determined. They are three levels higher than previously, i.e. ε_p^0 = 2.604 10^{-3} 1/s. Similarly as for lower strain rates ε_p^0, points for the matrix approximating the data set were identified using subprogram *Sftools* available in Matlab program.

The mathematical function for the J-C constitutive material model applicable for low and high strain rates is expressed by Eqn. (3) (case JC1 in Table 1) as follows

$$f(T,\varepsilon_p,\dot{\varepsilon}_p) = (1012 + 393 \cdot \varepsilon_p^{0.125}) \cdot (1 + 0.0271 \cdot \ln(\dot{\varepsilon}_p / \dot{\varepsilon}_p^0)) \cdot ((1 - ((T-20)/1255)^{2.42}) \tag{3}$$

The measured/predicted values of the cutting temperature recorded during finish turning operations of an Inconel 718 alloy with TiAlN coated carbide tools varied between 500°C and 700°C depending on cutting parameters used. Consequently, the appropriate J-C constitutive model was limited to the temperature range of T=400-700°C and, as a result, the mathematical function for the general J-C constitutive model valid for both low and high strain rates (case JC2 in Table 1) is defined by Eqn (4) as follows

$$f(T,\varepsilon_p,\dot{\varepsilon}_p) = (1012+511\cdot\varepsilon_p^{0.396})\cdot(1+0.0271\cdot\ln(\dot{\varepsilon}_p/\dot{\varepsilon}_p^0))\cdot((1-((T-20)/1255)^{4.33}) \qquad (4)$$

2.4. COMPARISON OF MATHEMATICAL FUNCTIONS OF J-C MODEL

The comparison of the experimentally derived model JC1 with the reference model A for the strain rate $\dot{\varepsilon}_p^0$ =2.604 10^{-3} 1/s is shown in Fig. 2.

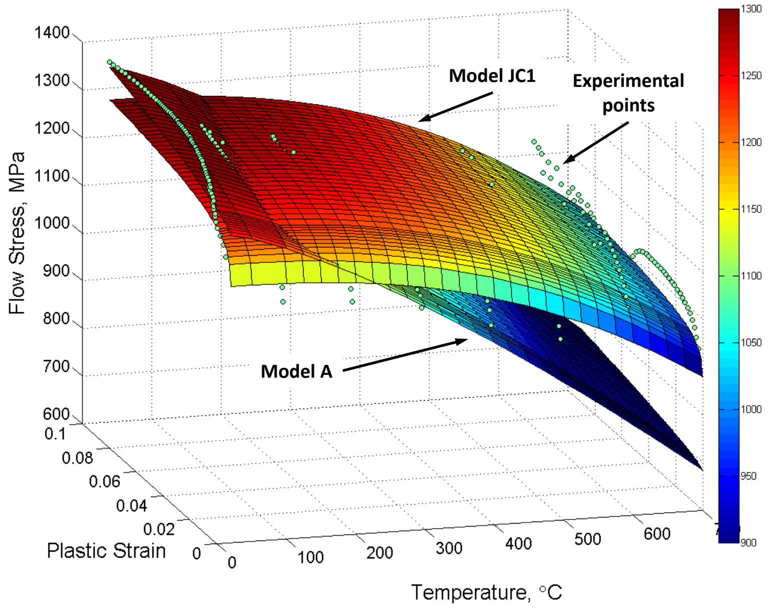

Fig. 2. Surface responses for reference model A and experimentally derived J-C model (model JC1) generated for T=20-700°C and $\dot{\varepsilon}_p^0$ =2.604 10^{-3} 1/s

Fig. 2 confirms a very good agreement for the reference temperature of T=20°C using reference model A. On the other hand, at testing temperatures above 600°C a good agreement for was achieved using both experimentally-based JC1 and JC2 models (Fig. 3).

It should also be noted in Fig. 2 that model A approximates better experimental points for lower temperatures of T=20-300°C. Based on these observations, the actual constitutive model JC was limited to the experimental points obtained for higher testing temperatures.

In addition, this comparison covers the modeling effects for the reference temperatures of T_0=20°C and highest temperatures as presented in Fig. 3. The R-square values for these two modeling cases for T=20-700°C and T=400-700°C are equal to 0.7554 and 0.7639 respectively. It should be noticed that the FEM simulations using the JC2 model are limited to temperatures higher than T>400°C. It results from the special mathematical description of the thermal softening module in the J-C model given by Eqn. 1 for which for $T< T_0$ and the exponent m being a rational number its computation is not possible. Taking into account small differences in the predicted values of the flow stress in this study the FEM simulations were carried out using the J-C model with the ambient T_0=20°C (case JC2 in Table 1).

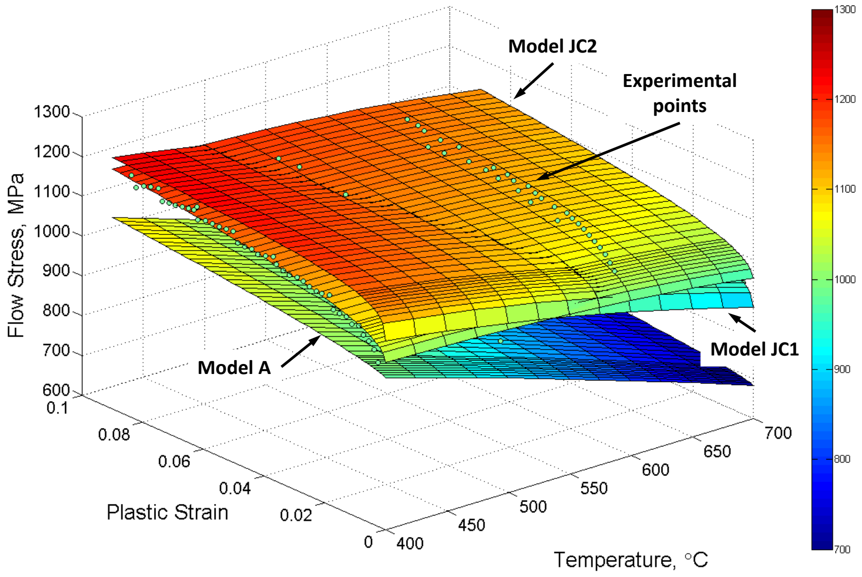

Fig. 3. Reference model A and experimentally-derived model JC1 for ambient temperature T_0=20°C and T=20-700°C and model JC2 for T_0 =20°C and T=400-700°C

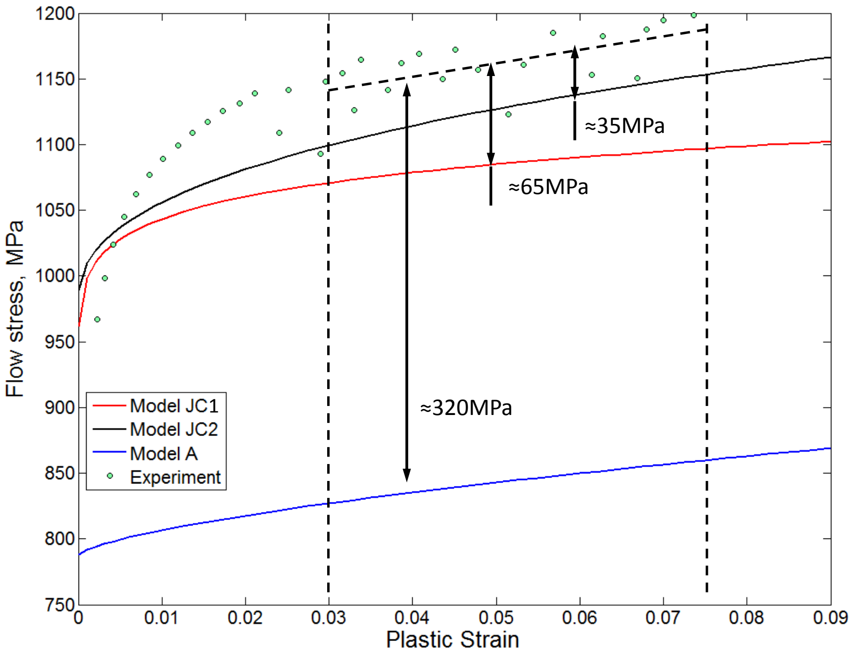

Fig. 4. Localization of the J-C models used versus experimental points for a low strain rate and temperature T=600°C

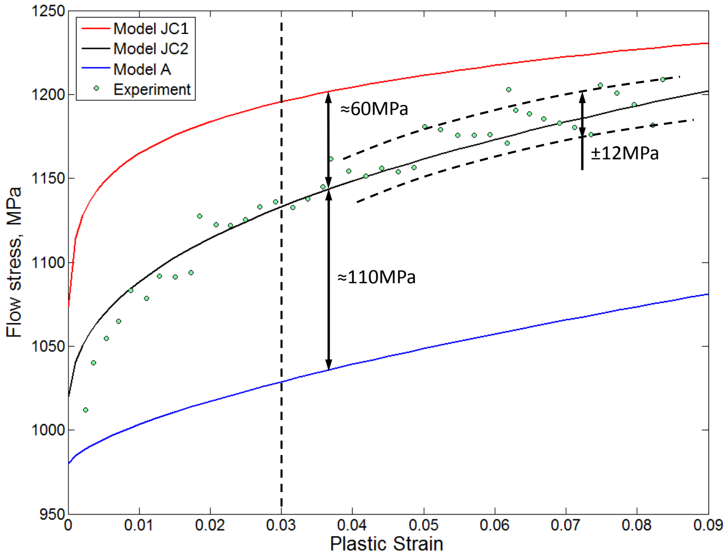

Fig. 5. Localization of the J-C models used versus experimental points for a low strain rate and temperature *T*=400°C

Fig. 4 compares predicted and experimental values of the equivalent flow stress determined for the temperature of 600ºC (this plot is the cross-section of three spatial surfaces in the stress-strain plane shown in Fig. 3). A similar temperature was measured in finish turning of an Inconel 718 alloy using the natural thermocouple technique. The accuracy the FEM predictions is discussed in details in Section 3.

As shown in Fig. 4 the best fitting of the experimental points to the mathematical model is observed for the cases JC2 for which the average variation is about 35 MPa (equivalently about 3% when the flow stress is about 1150 MPa). Appropriately, for the JC1 model the difference increases to about 65 MPa. In contrast, the model A predicts the measured flow stress with a distinctly higher variation of about 320 MPa (≈35%).

In particular, the best fitting of +/- 12 MPa was reached using JC2 model for T=400ºC, as illustrated in Fig. 5.

3. VALIDATION OF NEW MATHEMATICAL FUNCTIONS OF J-C MODEL BY FEM SIMULATION

The J-C constitutive models selected were validated for a finish turning operation with constant cutting parameters: the cutting speed of v_c=90 m/min, the feed rate of f=0.05 mm/rev and the depth of cut of a_p=0.125 mm.

The cutting tool inserts of CNMG 120412-UP type made of TiAlN coated sintered carbide (KC5010 grade by Kennametal) were used. FEM simulations were run for temperature-dependent values of the thermal conductivity and the specific heat available in [2].

Fig. 6 presents the records of temperature evolution obtained for differently parameterized J-C models with measured values represented by their average values (the temperature variation is 612±30ºC). It can be seen in Fig. 6 that the best agreement with the measured temperatures allows the JC1 model with the lowest values of B parameter and n exponent in the first elastic-plastic term. A similar effect but with visibly underestimated temperature values was obtained using the A model but with quite a different set of the model parameters. In contrast, for JC2 model the simulated temperatures overestimated the measurements even by 125ºC. Fig. 7 presents the predicted values of the three components of the resultant cutting force using JC1 and JC2 models and the A model corresponding to the estimated temperature.

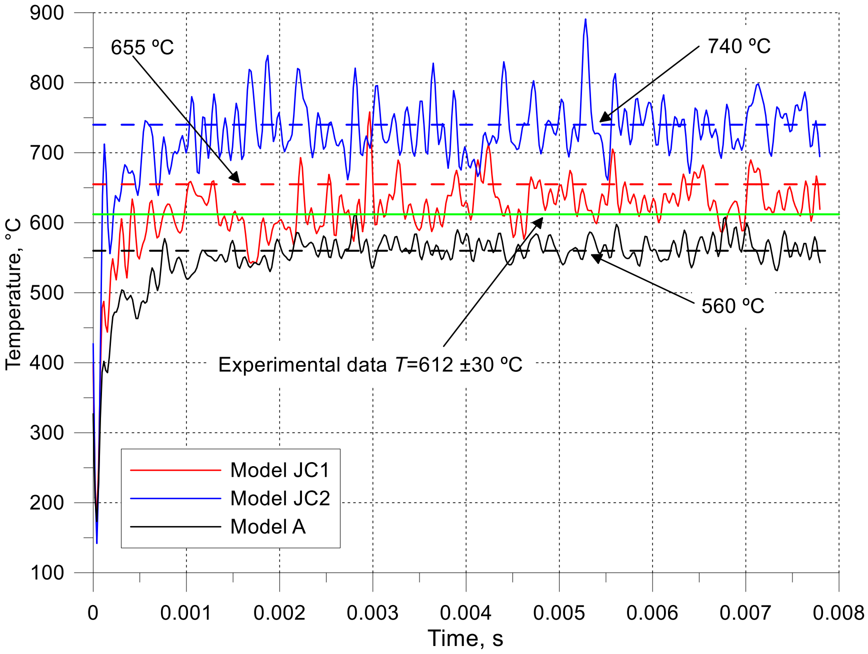

Fig. 6. Comparison of FEM predicted temperatures using different J-C models

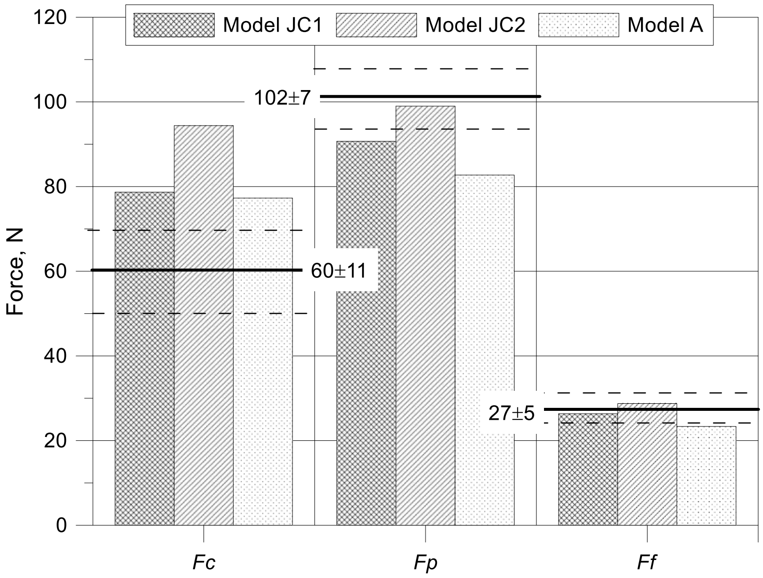

Fig. 7. Comparison of FEM predicted componential forces using different J-C models

It can be observed in Fig. 7 that the best prediction accuracy was obtained for both the passive F_p and feed F_f forces using JC2 type model. For these forces the average experimental and predicted values differ only by 1-2%. A worse result obtained for the cutting force F_c is probably due to an excessive strain-hardening effect reported by machinists working with difficult-to-machine alloys. As reported previously in introduction the accurate simulation of the F_c forces is performed using the J-C constitutive model proposed by Uhlman et al. [8,9] with evidently pronounced strain effect. For this model the highest value of B parameter in the first elastic-plastic term was selected.

4. CONCLUSIONS

1. In this study FEM simulations were carried out using the AdvantEdge package which requires the basic J-C model given by Eqn. 1 as the input. As a result, the experimentally-derived J-C models can be described by other mathematical functions and the obtainable accuracy is limited.
2. The experimentally-derived J-C models guarantee more accurate FEM predictions of the cutting temperature and componential cutting forces.
3. Important problem is an excessive strain-hardening effect encountered by machining difficult-to-machine alloys. In this case for experimentally-derived J-C constitutive model good agreement was achieved when used a highest values of B and m parameters in the elastic-plastic and temperature terms.
4. New J-C material models were derived using a special mathematical procedure and generation of a family of spatial surfaces characterized by different sets of A, B and C parameters, and m and n exponents.
5. In particular experimentally-derived J-C constitutive model denoted by symbol JC2 seems to be an optimal solution which allows an accurate prediction of the cutting temperature and the feed and passive forces with the prediction error of 1-2%.

ACKNOWLEDGEMENTS

A financial support of The National Centre for Research and Development Project No INNOLOT/I/9/NCBR/2013 "Advanced methods for manufacturing of aero engine case module components" - CASELOT is gratefully acknowledged. A financial support of The National Centre for Research and Development Project No INNOLOT/I/7/NCBR/2013 "Turbine for Turboshaft Engine Demonstrator" - TED is gratefully acknowledged.

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