Analysis of plastic properties of titanium alloys under severe deformation conditions in machining

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Abstract: The present paper presents a method of analysis of titanium alloys plastic properties under severe deformation conditions during milling with registration of the cutting force components Fx, Fy, Fz in real time using a special stand. The obtained constitutive relations in the form the Johnson-Cook law for stresses and dependence for a friction coefficient describing the titanium alloy VT9 plastic properties under simulate operating conditions.

Keywords: cutting temperature, cutting force, rheological properties, the stress-strain state, Johnson-Cook constitutive model.

1. INTRODUCTION

The operation life and the overhaul period of modern gas turbine engines (GTE) depends largely on the strength properties of compressor blades that operate under high static, dynamic and thermal loads. The operating characteristics of these products depend very heavily on the state of the surface layer, the structure of which is defined by a complex of its mechanical properties. Introduced in the process of finish machining plastic deformation has a great impact on plastic properties of a surface layer material, which significantly differ from the results obtained by standard regulated tests. Note that in the course of processing the zone of plastic deformation is localized near the cutting wedge, the cutting temperature gradient due to this localization is up to 300 ° C/mm for titanium alloys, the strain rate is up to 40000 s^{-1}, which causes a change in plastic and elastic-plastic properties of processed materials in a wide range.

Currently, there is inadequate availability of reliable experimentally-based data related to the rheological properties of processed materials under such specific conditions; therefore data related to plastic properties of materials under simulated operating conditions are very important.

The article deals with the method and the results of the titanium alloy plastic properties analysis under severe deformation by edge tool during machining using specialized force and a temperature measuring stand. The results are presented in the form of the Johnson-Cook dependence [1, 2], which establishes a link between the strain and the stress states. The dependences obtained can be used for FEM-simulation of edge cutting machining processes.

The finite element method (FEM), known from 1960-1970 [3] allows us to anticipate and solve the problem of optimization of cutting tool geometry analyzing cutting forces, stresses, tool wear and temperature. Its advantage is in solving of contact problems for dissimilar materials [4], in description of large deformations, including in the area of flow discontinuity, using a combined approach to Lagrange and Euler finite elements grid generation [5]. In order to provide an adequate simulation of any cutting process in such commercial products of FEM-analysis as Abaqus, Deform and Advant Edge [6] libraries of processed materials properties are used; these libraries set constitutive relations between stresses and strains. The most popular models for FEM-analysis of cutting process is Johnson-Cook models [7, 8, 9], the modified Johnson-Cook model [10, 11], the Zireli-Armstrong model [12], the Oxley model [7, 13], and others.

Note that during machining a large part of cutting force is spend on frictional energy dissipation over the contact surfaces between the cutting tool and the processed workpiece [14, 15]. In this connection, for adequate processes simulation in a processing zone it is important to know an actual friction coefficient at the contact surfaces depending on temperature and cutting deformation rate.

2. METHOD

The equipment used for the experiments:

- Vertical CNC milling machine ALZMETALLBAZ 15 CNC;
- Piezo-multicomponent dynamometer Kistler Type 9257B;
- Pyrometer IP 400;
- Tool: End carbide monolithic mill by Seco with diameter of 10 mm, number of teeth z = 4;
- Work-pieces (H x W x D): 6 x 24 x 40;
- Work-pieces material: titanium alloy VT9 as received and heat-treated;

For the experiment with the heat-treated VT9 material the samples made of the VT9 material were heat treated Using the following order: hardening at 920-940 °C during 1 hour, water quenching; age-hardening at 570 °C during 6 hour, air cooling.

In accordance with the extreme principles of continuum mechanics cutting power as a process of plastic deformation is defined by the following expression:

$$\dot{u}_p \le \iiint\limits_{W_{опд}} \sigma_{ij}\dot{\varepsilon}_{ij}^{\kappa} dW + \iint\limits_{A_{тр}} \mu(V_{деф})\sigma_s \Delta V_i^{\kappa} n_i dA, \quad (1)$$

where V_i^{κ} - kinematically admissible field of velocities in the focus of plastic deformation (FPD) with volume of $W_{ОПД}$;

$\dot{\varepsilon}_{ij}^{\kappa}$ - strain rate obtained on the basis of the kinematically admissible field of velocities;

ΔV_i^{κ} - slip velocity (relative movement of rubbing surfaces) over the surfaces with the total area of friction $A_{тр}$.

σ_s - yield point;

$\mu(V_{деф})$ - deformation velocity $V_{деф}$ dependant friction coefficient.

The first (1) term is the power of plastic deformation; the second one is the friction power dissipation. Let us express $\dot{u}_p$ in terms of the corresponding invariants of tensors σ_{ij} and $\dot{\varepsilon}_{ij}^{k}$ - intensity of the strain and stress rates σ_2 и $\dot{\varepsilon}_2^{\kappa}$ (and) :

$$\dot{u}_p \le \iiint\limits_{W_{опд}} \sigma_2\dot{\varepsilon}_2^{\kappa} dW + \iint\limits_{A_{тр}} \mu(V_{деф})\sigma_s \Delta V_i^{\kappa} n_i dA \quad (2)$$

Taking into account the mean-value theorem and considering the plasticity condition $\sigma_2 = \sigma_s(\varepsilon_2, \dot{\varepsilon}_2, T)$, we obtain:

$$\dot{u}_p \le \sigma_s(\varepsilon_2, \dot{\varepsilon}_2, T)\left[(\dot{\varepsilon}_2^{\kappa})_{сред} W_{ОПД} + \mu(V_{деф})(\Delta V^{\kappa})_{сред} A_{тр}\right] \quad (3)$$

Let's express mean values of $(\dot{\varepsilon}_2^{\kappa})_{сред}$ and $(\Delta V^{\kappa})_{сред}$ in terms of cutting speed (deformation) $V_{деф}$:

$$(\dot{\varepsilon}_2^{\kappa})_{сред} = V_{деф} \cdot (\dot{\varepsilon}_2^{\kappa})_{сред\ отн}$$
$$(\Delta V^{\kappa})_{сред} = V_{деф} \cdot (\Delta V^{\kappa})_{сред\ отн} \quad (4)$$

Relative values $(\dot{\varepsilon}_2^{\kappa})_{сред\ отн}$ and $(\Delta V^{\kappa})_{сред\ отн}$ are defined by FPD geometry, friction surfaces sizes and do not depend upon (deformation) speed $V_{деф}$. Let's write (3) in the following form:

$$\dot{u}_p \le \sigma_s(\varepsilon_2, \dot{\varepsilon}_2, T) \cdot V_{деф} \cdot (\dot{\varepsilon}_2^{\kappa})_{сред\ отн} W_{ОПД}\left[1 + \mu(V_{деф})K_{ОПД}\right], \quad (5)$$

where the dimensionless criterion $K_{ОПД} = \frac{(\Delta V^{\kappa})_{сред\ отн} A_{тр}}{(\dot{\varepsilon}_2^{\kappa})_{сред\ отн} W_{ОПД}}$, equal to the ratio of the relative friction power to the plastic deformation power characterizes geometric deformation conditions (FPD geometry and material velocity shape in FPD) regardless of the friction coefficient value .

In this case, if we accept that $\mu = \mu_{\max} = \frac{1}{\sqrt{3}}$, then from (5) it follows that, between the set elements $\{(\dot{\varepsilon}_2^{\kappa})_{сред\ отн}, V_{деф}, W_{ОПД}, K_{ОПД}, \sigma_s\}$ there is one-to-one dependence. Then $K_{ОПД}$ can be determined using the following correlation:

$$K_{ОПД} = \frac{(\dot{u}_p)_{\mu=\mu_{\max}} - 1}{\mu_{\max} \cdot (\dot{u}_p)_{\mu=0}} = \frac{(F_p)_{\mu=\mu_{\max}} - 1}{\mu_{\max} \cdot (F_p)_{\mu=0}} \quad (6)$$

Using the correlation (6) for $K_{ОПД}$ determination, an experiment on the basis of virtual simulation of cutting deformation process using Deform 3D software and two pre-set values of friction coefficient $\mu_{\max} = 0,577, \quad \mu = 0$ was carried out.

A process of cutting of a sheet with the height of *h=6mm* and with the cutting depth of *t=0.33mm* made of VT-9 alloy, having accepted in material properties σ_s - invar by T and $V_{деф} = const$.

Fig.(**1**) shows a graph of cutting forces according to the calculations made in Deform 3D at $\mu = 0,577$

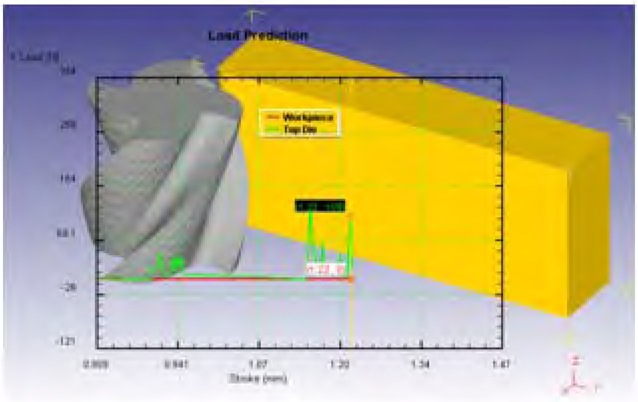

Fig. (1). Cutting force according to the calculations made in Deform3D at $\mu = 0,577$

According to (6), we have:

$$K_{ОПД} = \frac{109-1}{0,577 \cdot 45} = 4,15$$

At a certain value of $K_{ОПД}$ it is possible to obtain experimental plasticity conditions using the above mentioned equipment.

Let's consider two cases of deformation (cutting), with $V_{деф0}$ and $V_{деф1}$ velocities respectively, and with the rest similar process parameters. In this case, considering the fact that $V_{деф0}$ is selected so that $\sigma_s(\varepsilon_2, \dot{\varepsilon}_2, T) = \sigma_s(\varepsilon_2), \quad \mu(V_{деф0}) = 0,577$,

i.e. they reach their maximum values, the following relationship is correct:

$$\frac{F_{p1}}{F_{p0}} = \frac{(\dot{u}_p)_1 / V_{деф1}}{(\dot{u}_p)_0 / V_{деф0}} = \frac{\sigma_s(\varepsilon_2, \dot{\varepsilon}_2, T) \cdot \left[1+\mu(V_{деф1})K_{ОПД}\right]}{\sigma_s(\varepsilon_2) \cdot \left[1+0,577K_{ОПД}\right]}, \quad (7)$$

where F_{pi} - cutting force.

If we represent the constitutive equations in the following form:

$$\sigma_s(\varepsilon_2, \dot{\varepsilon}_2, T) = \sigma_s(\varepsilon_2) f(\dot{\varepsilon}_2, T), \quad (8)$$

i.e. in the form of the product of 2-functionals $\sigma_s(\varepsilon_2)$ - strain hardening and $f(\dot{\varepsilon}_2, T)$ - temperature and speed softening, then based on the relationship (7) we can obtain the experimental conditions of the determination $f(\dot{\varepsilon}_2, T)$ and the friction law $\mu(V_{деф})$ when cutting with different velocities $V_{деф}$

$$\frac{F_p}{F_{p0}} = \frac{f(\dot{\varepsilon}_2(V_{деф}), T)\left[1+\mu(V_{деф})K_{ОПД}\right]}{\left[1+0,577K_{ОПД}\right]} \quad (9)$$

3. RESULTS

Table 1 shows the results of the full factorial experiment of measurement of cutting force and cutting temperature during milling of a plate 6mm high made of titanium alloy VT9. An example of the experimentally determined force curve is shown in Fig. (2).

Table 1. Relative cutting forces during milling of titanium alloy VT9 as received (*side milling t=6mm, a=0.1…0.3mm, Vдеф=60m/min, 100 m/min*)

#	Relative force, $\frac{F_p}{F_{p0}}$	Relative speed, $\frac{V_{деф}}{V_{деф0}}$	Relative temperature, $\frac{T-20}{1490}$
1	1,000	1,000	0,206
2	1,000	1,000	0,263
3	1,007	0,600	0,268
4	1,083	0,600	0,345
5	1,000	1,000	0,388
6	1,000	1,000	0,536
7	1,041	0,600	0,504
8	0,808	0,600	0,675

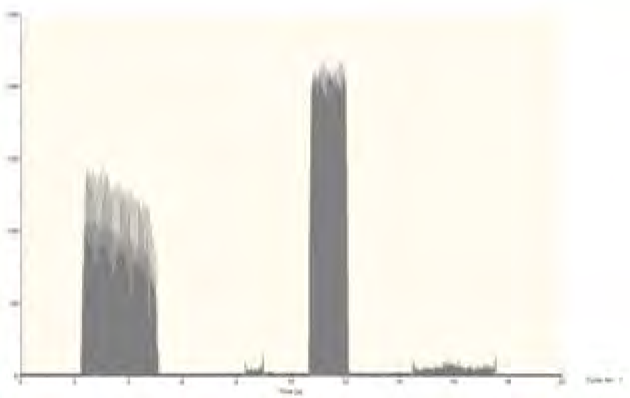

Fig. (2). Observed dependence of the resultant cutting force

In conditions of uncertainty with respect to the friction coefficient it will be appropriate to set a friction model of the following form:

$$\tau_{mp} = \mu\sigma_s(\varepsilon_2,\dot{\varepsilon}_2,T) = \frac{\sigma_s(\varepsilon_2,\dot{\varepsilon}_2,T)}{\sqrt{3}}\left[1 - K\ln\left(\frac{V}{V_{\max}}\right)\right], \quad (10)$$

For our case we determine the law of friction coefficient variation using the following correlation:

$$\mu(V_{деф}) = \frac{1}{\sqrt{3}}\left[1 - a_4\ln\left(\frac{V_{деф}}{V_{деф0}}\right)\right], \quad (11)$$

where the constant $\mu = \frac{1}{\sqrt{3}} \approx 0{,}577$ corresponds to the maximum friction value at pure shift, which occurs when the cutting(deformation) speed value is $V_{деф0}$ and the experimentally determined coefficient a_4 characterizes a degree of approximation of the friction coefficient to its maximum value with increasing cutting speed.

Let's define $f(\dot{\varepsilon}_2,T)$ in (8) within a constant factor a_0 so that based on the processing of experimental results we could get one of the laws that regulate the constitutive relations $\sigma_s(\varepsilon_2,\dot{\varepsilon}_2,T)$. Using the notation of the Johnson-Cook law, we can write:

$$f(\dot{\varepsilon}_2,T) = a_0\left(1 + a_1\ln\left(\frac{V_{деф}}{V_{деф0}}\right)\right)\left(1 - a_2\left(\frac{T-T_к}{T_{пл}-T_к}\right)^{a_3}\right), \quad (12)$$

Using (9), (10), (11), we obtain a law for processing of the data shown in Table 1:

$$z = \frac{F_p}{F_{p0}} = a_0\left(1 + a_1\ln\left(\frac{V_{деф}}{V_{деф0}}\right)\right)\left(1 - a_2\left(\frac{T-T_к}{T_{пл}-T_к}\right)^{a_3}\right)\left(1 + \frac{K_{ОПД}}{\sqrt{3}}\left[1 - a_4\ln\left(\frac{V_{деф}}{V_{деф0}}\right)\right]\right), \quad (13)$$

Where $T_к$ =20˚C; $T_{пл}$=1500˚C; $K_{ОПД}$ = 4.15; $V_{деф}$=100 *м/мин*

As a result of statistical processing of the data given in Table 1 a nonlinear regression model according to the correlation (13) is obtained; its coefficients and the response surface is shown in Fig. (3). The degree of reliability of the model is 96.4%.

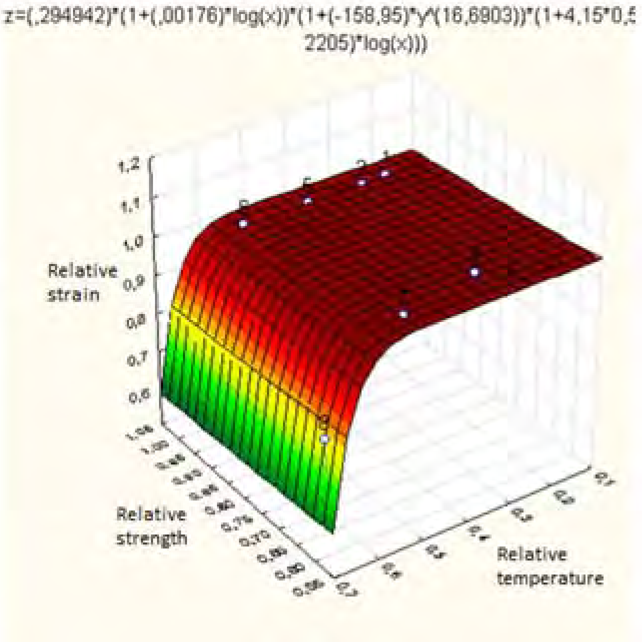

Fig. (3). Response surface and regression model of relative efforts in high-speed milling of titanium alloy VT9 as-received.

According to (8) for a given functional $f(\dot{\varepsilon}_2, T)$ one unknown value $\sigma_s(\varepsilon_2)$ remained, and this value determines the stress state-strain state dependence $\sigma_s = \sigma_s(\varepsilon_2)$.

To find this dependence we use statistical data for material VT9, provided in the library of materials of the software Deform 3D, for high-speed machining conditions with a range of intensities of strain rates of 0 ... .100000s^{-1} for the temperature $T_к$=*20˚C*.

The experimental points are shown in Fig. (4).

The curve approximating these experimental data was obtained by the simplex method with disparity determined by the least square method in the form of the correlation:

$$\sigma_s(\varepsilon_2) = (A + B\varepsilon_2{}^n) \qquad (14)$$

The resulting curve and coefficients of the model (14) are also shown in Fig. (4). The degree of reliability of the approximation is 84%.

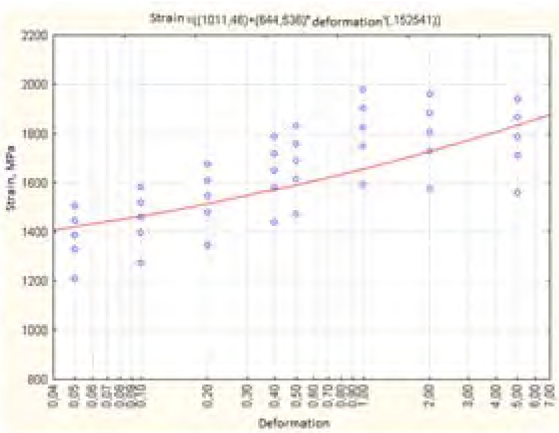

Fig. (4). Average stress-strain state dependence at the intensity range of strain rate of 0 ... .100000s^{-1}.

4. DISCUSSION

In the CAE system Deform 3D plastic properties of a material in the form of the Johnson Cook master curve are written in the form [2]:

$$\sigma = (A + B\varepsilon_2{}^n)\left(1 + C\ln\left(\frac{\dot{\varepsilon}_2}{(\dot{\varepsilon}_2)_0}\right)\right)\left(\frac{\dot{\varepsilon}_2}{(\dot{\varepsilon}_2)_0}\right)^{\alpha}\left(D - E\overline{T}^{m}\right), \qquad (15)$$

$$\overline{T} = \frac{T - T_0}{T_{плав} - T_0}, \quad \mathrm{D{=}D_0 exp(k(T{-}T_{\mathit{b}})^{\beta})}$$

In this case, in accordance with the obtained coefficients A, B, n and a_0 ... a_4 coefficients of the Johnson-Cook model will take the values shown in Table 2.

Table 2. Values of coefficients of the Johnson-Cook plastic properties model for VT9 alloy during processing at high speed.

A	1011,4600
B	644,5360
n	0,1525
C	0,0018
$\dot{\varepsilon}_o$	50000,0
$E = \frac{a_2}{a_0}$	538,9195
$D = \frac{1}{a_0}$	3,3905
$m = a_3$	16,6903
k	0

It is known that by changing the friction process nature, the cutting force condition in the cutting zone during chips formation is changed as a consequence of changing of the plastic deformation zone form. Numerical simulation of chip formation in CAE- Deform for different friction coefficient values allows to virtually estimate which part of energy is consumed by plastic deformation, and which - by friction power dissipation along chip-tool contact surfaces. In actual practice of cutting the friction coefficient value along the surface is not constant but depends on the contact pressure and on the temperature and speed factor in the cutting zone. Functionally the defined model of the friction coefficient changes with unknown parameters can be determined experimentally by the above procedure, taking into account evaluation of the indicated energies correlations calculated by numerical methods. This is the essence of the proposed in this article method.

5. CONCLUSION

Thus, for the titanium alloy VT9 as-supplied for high-speed cutting (milling)conditions the laws of plastic properties (constitutive relations) in the form of the Johnson-Cook correlation and the law of friction coefficient variation with cutting speed were established.

$$\sigma_s = \left(1011,46 + 644,536\varepsilon_2{}^{0,1525}\right)\left(1 - 0,0018\ln\left(\frac{\dot{\varepsilon}_2}{5000}\right)\right)\left(3,3905 - 538,9195\left(\frac{T-20}{1480}\right)^{16,6903}\right)$$

$$\mu = 0,577\left(1 - 0,12205\ln\left(\frac{V_{деф}}{100}\right)\right) \qquad (16)$$

The resulting constitutive relations (16) in the form of the Johnson-Cook law for stresses and the correlation for the friction coefficient describe the plastic properties of the titanium alloy VT9 in conditions close to the technological which are characteristic of high-speed machining.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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