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Procedia Engineering 150 (2016) 866 – 870

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Industrial Engineering, ICIE 2016

Numerical Simulation of the Aluminum 6061-T6 Cutting and the Effect of the Constitutive Material Model and Failure Criteria on Cutting Forces' Prediction

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Abstract

Numerical simulation of cutting by means of finite element methods is widely accepted worldwide. Simulation results hardly depend on the right choice of input material parameters such as the material model, the hardening law and failure criteria. One of the methods that have proved their adequacy is lagrange with erosion. Its drawbacks are widely known, but for simulation of ductile material machining this method seems to be the most reliable. The aim of the present paper is to assess material model parameters and failure criteria on cutting forces arising in the cutting process of 6061-T6 aluminum. Material model parameters were specified as the Johnson-Cook material model, the kinematic hardening and the isotropic hardening. The failure criteria were the Johnson-Cook model, the equivalent plastic strain and the maximum principal strain.

Peer-review under responsibility of the organizing committee of ICIE 2016

Keywords: finite elememt method; cutting simulation; hardening; failure criteria.

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1. Introduction

Cutting is one of the widespread methods of machining of different materials. Prediction of cutting forces plays an essential role for quality improvement of machined parts and components. Cutting can be analyzed by analytical and numerical methods. Numerical methods currently are widely improved; one of those is finite element method [20]. This method is widely used in various formulations such Lagrangian [1, 2, 13,8], Eulerian [6], SPH [3,12,14],

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Peer-review under responsibility of the organizing committee of ICIE 2016
doi:10.1016/j.proeng.2016.07.031

SPG [18], EFG [17] and incorporated in number of commercial programs. The main issue of using such a method for cutting simulations is the reasonable choice of parameters: material model, mechanical material properties and failure criteria [5, 8–12, 15, 16]. These parameters make an essential effect on obtained results, as in terms of quantity, as in terms of quality.

The aim of the current paper is to assess effect of material model parameters and failure criteria on cutting forces arising in the cutting process during finite element method simulation. For this purpose, the authors have developed a finite element model of free orthogonal cutting of aluminum 6061-T6.

2. Finite element modeling of free orthogonal cutting

2.1. Model description

For finite element modeling of free orthogonal cutting the model was created with the following parameters: box-shaped workpiece with 10 x 4 x 3 mm. In analysis, cutting tool is assumed to be a rigid body with following parameters: elastic modulus 650 GPa, Poisson's ratio 0.25. Geometric variables of the tool are as follows: tip radius r= 0.1 mm, rake angle $\gamma = 15^0$, clearance angle $\alpha = 5^0$. Cutting speed 10 m/s, cutting depth t= 1 mm. The material aluminum 6061-T6 has the following properties: density 2700 kg/m3, Young's modulus E=70 GPa, fracture strain 0.5, yield stress 260 MPa. Coulomb's friction coefficient between tool and workpiece equals 0.3. The finite element model of workpiece was using uniform mesh of hexahedral elements. The mesh of tool is not uniform for better results prediction. The analysis was performed using finite element method with Langrangian approach, element erosion and deletion with failure strain 0.5.

2.2. Material models and failure criteria

Flow stress modeling of work piece material is very important to achieve satisfactory results from metal cutting simulation. In the analysis, 6061-T6 is selected as work piece material as its properties are widely estimated in literature. Isotropic hardening, kinematic hardening and Johnson-Cook constitutive models are used in the current analysis. The parameters for isotropic and kinematic hardening are as follows: elastic modulus 70 GPa, Poisson's ratio 0,33, yield stress 260 MPa. The parameters of Johnson-Cook obtained by experiment are as follows: A=324.1 MPa, B=113.8 MPa, N=0.42, C=0.002, M=1.34, strain rate effect is not considered [6,19]. The failure model parameters for Johnson-Cook model are as follows: D_1=–0.77, D_2=1.45, D_3=–0.47, D_4=0, D_5=1.6 [4, 6]. For kinematic and isotropic hardening two types of failure criteria are used: effective plastic strain 0,5 and maximal principal strain at failure. The former is always a positive value and accounts all strain components of the deformed state. The latter is a tensile strain indicator. Its use gives more satisfactory results as material failure always accompanied by advancing crack in which the principal stress is maximal. Von Mises stress distributions obtained in the result of modeling can be seen in Fig. 1. As one can see, the model elements have essential hourglass distortion that requires an additional investigation.

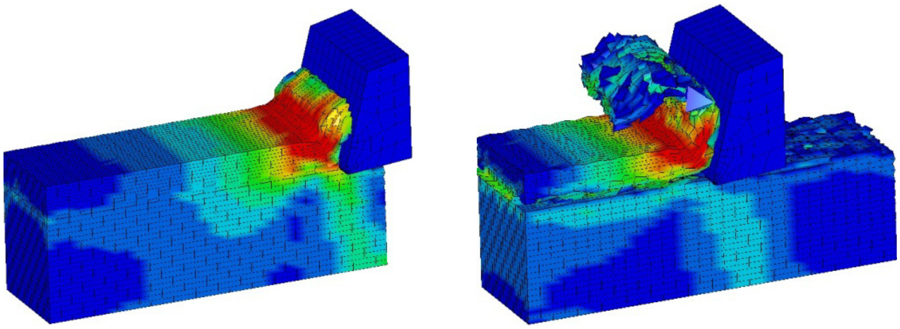

Fig. 1. Von Mises stress distribution using Johnson-Cook material model of aluminum 6061-T6

2.3. Cutting forces investigation

In this section the results of finite element simulation are presented. The cutting forces simulation results available in the literature are compared. As is known, cutting force has three components: tangential "cutting" force F_c, radial force F_r and axial or thrust force F_t. In free orthogonal cutting only two of them have meaning - F_c and F_t. Experimental results for investigated material 6061-T6 are given in table 1 [7]. The cutting conditions are as follows: cutting depth 0.63 mm, cutting width 3,3 mm, cutting velocity 20 m/s, rake angle 15°.

As mentioned, three different constitutive models are used in this study. Threes simulations are carried out using same friction model and coefficient. Effect of material constitutive models on cutting and thrust force is given in fig. 2-4. It can be stated that Johnson-Cook model can predict cutting force more accurate in contrast to other two. All models underestimate tangential forces.

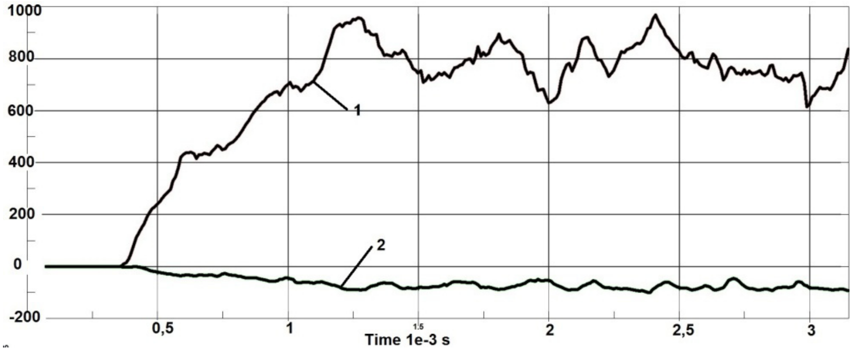

Fig. 2. Cutting forces F_c (1) and F_t calculated results (Johnson-Cook material model and criteria)

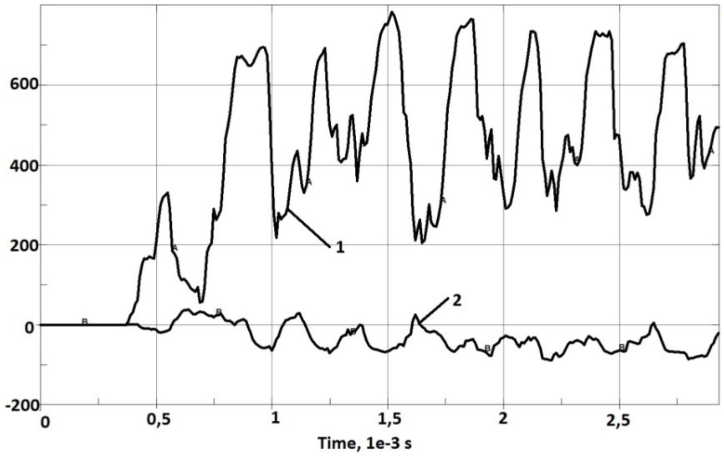

Fig. 3. Cutting forces F_c (1) and F_t calculated results (kinematic hardening material model and effective plastic strain failure criteria)

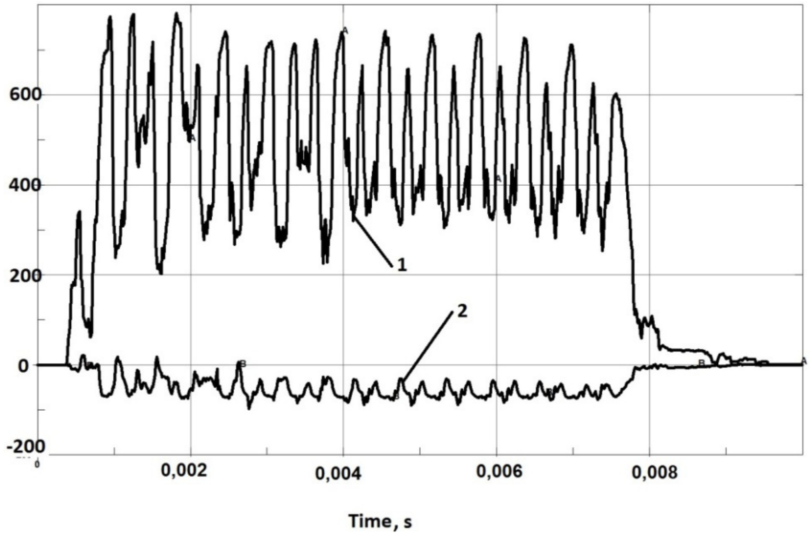

Fig. 4. Cutting forces F_c (1) and F_t calculated results (isotropic hardening material model and effective plastic strain failure criteria)

In order to estimate failure criteria on cutting forces value one simulation was carried out with maximum principal strain failure criteria using kinematic hardening material model. According to this criteria the finite element is excluded from calculation if this condition is satisfied: $\varepsilon_1 > \varepsilon_{max}$. Thus predicted cutting forces results are given in table 1.

3. Results and discussion

Numerical simulation of 6061-T6 aluminum free orthogonal cutting showed the following results. Overall approach to such a problem with finite element method proved its validity. Quantitive results are satisfactory as continuous chip is obtained during simulation. Cutting and thrust force are depending of constitutive models. Calculated results of cutting forces are given in Table 1. In all three cases thrust forces are underestimated. The minimum deviation is with Johnson–Cook constitutive model and failure criteria (800 N predicted), in this case the cutting force is overestimated. The maximum discordance is in case of kinematic hardening and effective strain failure criteria. Isotropic and kinematic hardening have practically the same results. The type of failure criteria has an essential effect on cutting forces values. The Johnson-Cook criteria can predict cutting force more accurate in contrast to other two. The difference between calculated and experimental cutting force may be attributed to simplified friction model with Coulomb's coefficient of friction.

Table 1. Cutting force and thrust force results for different material models and experimental data

Cutting forces, N	Experimental	Johnson-Cook	Kinematic hardening with maximum principal strain failure criteria	Kinematic hardening	Isotropic hardening
F_c	719	800	410	490	510
F_t	223	90	80	52	51

4. Conclusions

In this paper a finite element model of free orthogonal cutting of aluminum 6061-T6 is presented. The developed model is able to predict cutting forces and continuous chip morphology in full accordance with experimental data. Three different material models are implemented and results of modeling are compared with experimental data available in literature.

The results of the simulation show that Johnson-Cook constitutive model and failure criteria are able to give more accurate results than kinematic and isotropic hardening.

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