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An Investigation on Forces during End Milling Process Considering Different Failure Criteria

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Abstract

In present research, 3D FE model has been proposed to investigate cutting forces considering different failure criteria during end milling process. It is desirable to understand the cutting forces acting on the tool during ongoing process of machining to understand the tool wear, surface finish etc. for different material conditions. In this regard, material failure is quite important as the forces are mainly depending on the failure mechanism. Further, failure characteristics are difficult to analyze experimentally due to multi physics environment. Therefore, simulation model could be an appropriate method to predict the forces. In present study, Johnson-Cook (J-C) failure model has been used for two different mechanisms i.e. J-C ideal plastic and J-C dynamic shear. The Johnson Cook ideal plastic model uses together von mises yield surface and associated flow which is ideal to handle strain rate of high magnitude for deformation metals. The Johnson-Cook dynamic failure model consists of equivalent plastic strain at integration points of the elements; when the damage parameter (strain) exceeds than unity, failure occurs. The debonding and chip formation is modelled depend on the VCCT (Virtual Crack Closure Technique). The C3D8R element with ALE (Arbitrary Lagrangian Eularian) adaptive meshing used for prevention of severe mesh distortion. The work material selected as AISI 4340 due to its wide applicability in majority of the domains like aerospace (aircraft landing gear), automotive (power transmission systems), oil and gas drilling etc. Based on analysis of both the models, critical observations are reported and discussed.

Keywords: End Milling, Failure Criteria, Forces, ABAQUS.

1. INTRODUCTION

Since the 1800s, milling process has been used very widely which abrades the material with the help of friction or erosion. There are different milling processes developed today depending upon the application and type of the product and one of them is “End Milling”. This process differs from the other milling processes due to the type of tool involved in it. In this process the cutting teeth on end and side of the mill. Profile milling, tracer milling, shape milling, face milling and plunging are the typical application of the End mills. There are many important points of the process like chip formation, chip breakage, chip curling, built-up-edge, burr, chatter, tool wear, temperature of cutting operation and cutting forces as well.

A lot of study has been done experimentally to understand the mentioned important aspects of the end milling process but due to constrains offered by cost and material experimental studies are not always feasible. Such limitations have given rise to the usage of alternatives like Finite Element Method (FEM) which can be adopted along with advance numerical techniques and powerful computer systems. With the help of FEM the prediction of forces, temperature involved in the process, stress and strain developed during the process can be easily identified. Saffar et al (2008) [1] has already reported about the methods to define chip and tool interaction, threshold values to be given during the simulation in order to determine the feed force and chip geometry, the cutting force, the distribution of temperature and produced local stress. Pantel et al (2012) [2] performed simulation of shoulder milling operation on AISI 304 stainless steel using LS-DYNA. Penalty contact algorithm along with lagrangian formulation was adopted. Machinability of the material was studied by performing many experiments and compared with the simulation results in which material behaviour were modelled using the classical Johnson–Cook law. Sadeghinia et al (2007) [3] also adopted the Johnson-Cook work material model for behaviour of the material while performing and 2D simulation using ABAQUS/Explicit. In the developed model thermo-mechanical coupling, dynamic effects, constitutive damage law and effect of friction was also considered. As a chip criteria Johnson-Cook damage constitutive law was adopted and a good agreement was observed for the results of cutting force prediction. Özel and Altan (1998) [4] developed a FE model to determine the flow stress of the work material at high deformation rate and temperature which takes place in the cutting zone in order to determine the friction at the chip tool interface. Soo et al (2004) [5] developed a 3D FE model considering Lagrangian code in order to simulate the ball nose milling process in ABAQUS Explicit for Inconel 718 work piece material. During the simulations elastic–plastic inherent relationship was adopted for the work piece material and cutting forces and temperatures were predicted which was found to be in good accordance with the experimental results. Constantin et al (2010) [6] described the importance and effects of aspects like material properties, contact definition, rigid body considerations, thermo-mechanical algorithms and meshing methods during FE analysis of milling operation. Jin and Altintas (2012) [7] predicted the forces during the micro milling of brass 260 by FE model and slip line field simulation. Some limitations were observed in the friction model regarding predicting the feed forces during the simulation. Thepsonthi and Özel (2013) [8] adopted FEM to compare cBN coated and uncoated end mill cutters in terms of burr formation, surface discontinuities and wear of tool during titanium alloy micro machining.

However, the effect of different failure criteria hasn’t been addressed yet in order to study the forces encountered on the cutting tool. Therefore present study has been carried out

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considering different failure criteria using finite element analysis.

2. FINITE ELEMENT ANALYSIS

2.1. Modeling

The geometry and the assembly modeling are shown in Fig.1 and Fig. 2 respectively. The cutting tool is modeled as rigid body to reduce computational time. The Workpiece was modeled by the continuum solid part with 100000 C3D8R elements. The workpiece material used in this reported work is is AISI 4340 steel. Two isotropic constitutive material model were used i.e. J-C ideal plastic and J-C dynamic shear.

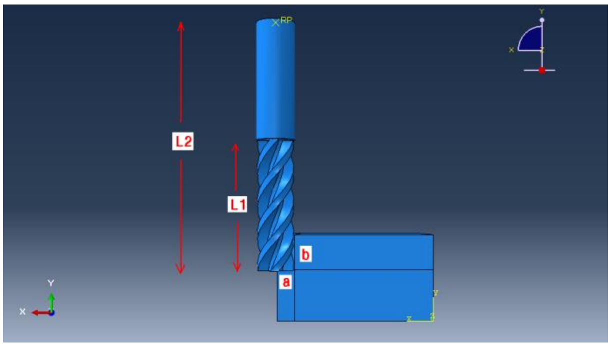

Fig. 1. Geometry modeling

The geometrical parameters are [1]: a=1.5mm, b=3mm, L1=11mm, L2=22mm, =3mm and flute count = 4

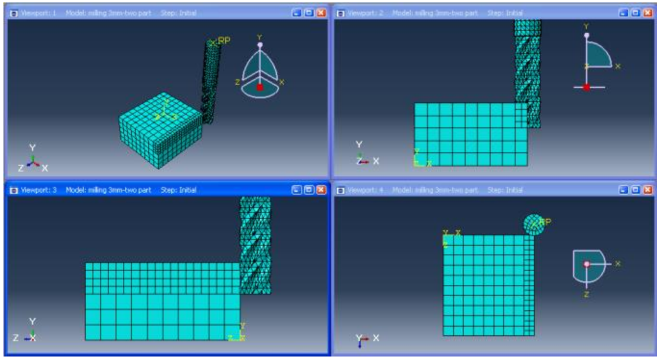

Fig. 2. Assembly modeling

2.2. Material Constitutive Model

In the reported work Johnson-Cook failure model is adopted along with a Mises yield surface and associated flow. Johnson-Cook hardening describes one type of isotropic hardening in which the static yield stress can be given by:

$$\sigma^0 = \left[A + B\left(\bar{\varepsilon}^{pl}\right)^n\right]\left(1 - \hat{\theta}^m\right) \tag{1}$$

Where, equivalent plastic strain is denoted as $\bar{\varepsilon}^{pl}$ and A, B, n and m are parameters of material measured at or below the transition temperature, T_{room}. $\hat{\theta}$ indicates the non-dimensional temperature given by:

$$\hat{\theta} \equiv \left\{\begin{array}{cc} 0 & for\ \ T < T_{room} \\ (T - T_{room})/(T_{melt} - T_{room}) & for\ \ T_{room} \le T \le T_{melt} \\ 1 & for\ \ T > T_{melt} \end{array}\right\} \tag{2}$$

Where, current temperature, melting temperature and transition temperature are denoted by T, T_{melt}, T_{room} respectively defined by the expression of yield stress at no temperature dependence. The parameters of the material are required to be measured below or at transition temperature.

When Johnson-Cook plastic dependent to strain rate, the yield stress is expressed as

$$\bar{\sigma} = \left[A + B\left(\bar{\varepsilon}^{pl}\right)^n\right]\left[1 + C\ \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right]\left(1 - \hat{\theta}^m\right)$$

(3)

where $\dot{\varepsilon}_0$ and C are material parameters.

The material parameters for AISI 4340 steel as following [3]. A = 1150 Mpa, B = 739 Mpa, C = 0.014, m = 1.03, n = 0.26, $\dot{\varepsilon}_0 = 1$, $T_{melt} = 1450\ °C$, $T_{room} = 20$, $E = 208000MPa$, $\nu = 0.3$, $\rho = 7.85e - 6kg/mm^3$

2.3. Failure Criteria

1) J-C Ideal Plastic

The Johnson-Cook plasticity model is also known as an Ideal plastic model. This model can be adopted along with failure model and the progressive damage. The general contact surfaces are modeled as bonded for potential crack surfaces. For the same, surface based cohesive behavior was modeled. Therefore, the implementation is carried out as pure master-slave formulation during 3D analysis. To identify the crack tip, an assumption was made that, predefined crack surfaces was initially bonded in Abaqus/Standard.

2) J-C Dynamic Shear

The Johnson-Cook dynamic failure model is based on the plastic strain value at the integration points of the elements. In this criterion, failure starts when the damage parameter (strain) exceeds than unity. Following equation defines the damage parameter w [2]:

$$w = \sum\left(\frac{\Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_f^{pl}}\right) \tag{4}$$

Where, $\Delta\bar{\varepsilon}^{pl}$, $\bar{\varepsilon}_f^{pl}$ is an increment of the plastic strain (equivalent) and the failure strain respectively and the summation is executed over all increments in the analysis. The strain at failure, $\bar{\varepsilon}_f^{pl}$, is assumed to be dependent on a non-dimensional plastic strain rate, $\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}$; a dimensionless pressure-deviatoric stress ratio, $\frac{p}{q}$ (where p and q is the pressure stress and the Mises stress respectively); and the non-dimensional temperature, $\hat{\theta}$, defined earlier in the equation 2.

The dependencies are assumed to be separable and are of the form

$$\bar{\varepsilon}_f^{pl} = \left[d1 + d2\ \exp\left(d3 \frac{p}{q} \right) \right] \times \left[1 + d4\ \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0} \right) \right] \left(1 + d5\ \hat{\theta} \right) \qquad (5)$$

Where, $d1 \sim d5$ are parameters of failure which can be measured at the transition temperature and $\dot{\varepsilon}_0$ is the reference strain rate. These are the material specific data, in present case those were taken from [3]. This criterion reaches, it is required to set the Deviotric stress component as zero for rest of the analysis.

2.4. Boundary conditions

The de-bonding and chip formation is modeled based on the VCCT (virtual crack closure technique). ALE (arbitrary lagrangian eularian) adaptive meshing technique is applied to the chip part in order to prevent the element distortion according to the high revolution speed of cutting tool. The coulomb friction parameter is assumed in this model in order to model contact zones between the tool and the chip as well the work piece and tool.

The contacting bodies will be assumed sticking together if $\|T_t\| < \mu\ |T_n|$ and in sliding if $\|T_t\| = \mu\ |T_n|$ with T_t and T_n representing the tangential and normal components of the surface traction at the interface and μ is assumed as a constant. Bottom of the work piece is perfectly fixed. A value of $\mu = 0.32$ is assumed. For the feed rate and cutting speed (revolution speed), were [1],

$V_Z = 25\ mm/\min = 0.4167\ mm/s$

$\omega_Y = 23.56\ m/\min = 42\ rev/s\ =\ 264\ rad/s$.

3. RESULTS AND DISCUSSION

Figure 3 and 4 indicates the force acting on the cutting tool predicted by dynamic shear and ideal plastic failure criteria. It can be clearly observed that the ideal plastic failure criteria under predict the forces.

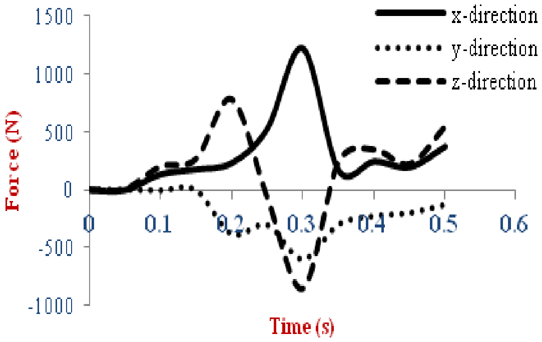

Fig. 3. Forces acting on cutting tool (Dynamic Shear)

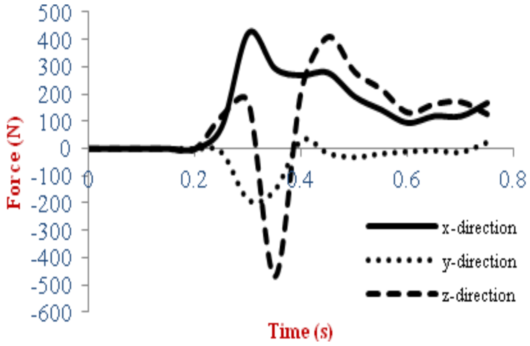

Fig. 4. Forces acting on cutting tool (Ideal Plastic)

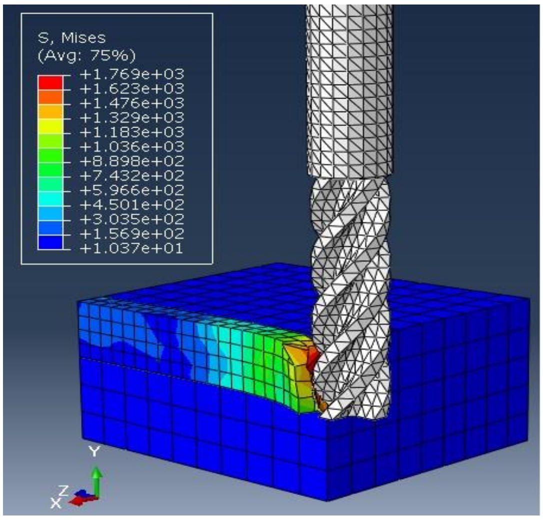

Fig. 5. Von-mises stress (Dynamic Shear)

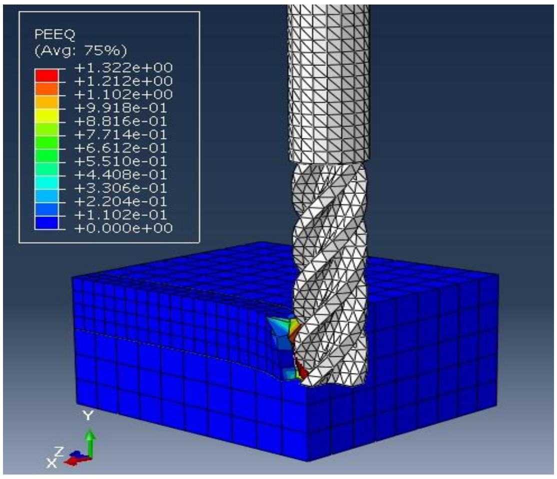

Fig. 6. Equivalent plastic strain (Dynamic Shear)

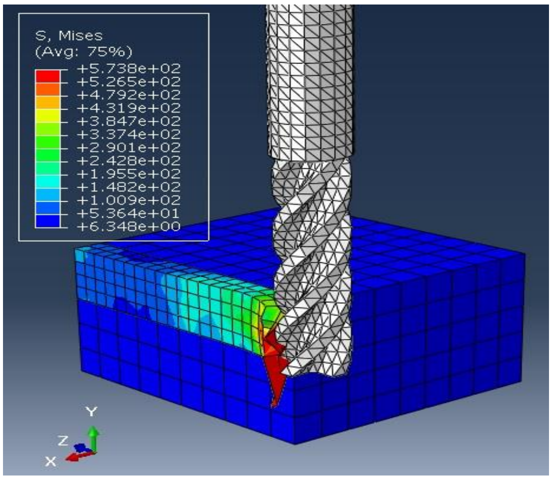

Fig. 7. Von mises stress (Ideal Plastic)

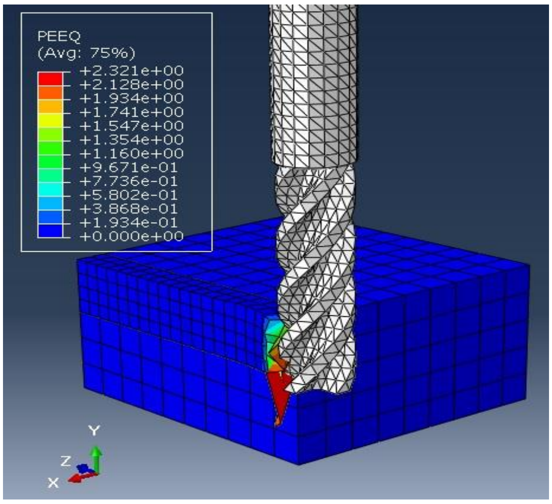

Fig. 8. Equivalent plastic strain (Ideal Plastic)

From comparison (figure 6 to 8) of results of equivalent plastic strain and Mises stresses it can be observed that mises stresses are under predicted by ideal plastic criteria. For PEEQ strain the value predicted by ideal plastic criteria is higher than that of dynamic shear criteria.

4. CONCLUSIONS

From the reported numerical investigation, it can be concluded that the FE method can successfully used to predict the cutting force exerted on the tool which is a very handy tool in comparison with the experimental methods which are costly and time consuming. Particularly regarding the force prediction in the reported work, the dynamic criteria gives the better results by predicted the higher magnitude of the force exerted on the tool. This gives exact prediction of force to the engineers which can lead to proper design of tool and selection of better experimental condition which will indirectly lead to satisfy the requirement of application.

References

[1] Saffar, R.J., Razfar, M.R., Zarei, O. and Ghassemieh, E., 2008. Simulation of three-dimension cutting force and tool deflection in the end milling operation based on finite element method. *Simulation Modelling Practice and Theory*, *16*(10), pp.1677-1688.

[2] Maurel-Pantel, A., Fontaine, M., Thibaud, S. and Gelin, J.C., 2012. 3D FEM simulations of shoulder milling operations on a 304L stainless steel. *Simulation Modelling Practice and Theory*, *22*, pp.13-27.

[3] Sadeghinia, H., Razfar, M.R. and Takabi, J., 2007, December. 2D finite element modeling of face milling with damage effects. In *3rd WSEAS international conference on applied and theoretical mechanics, Spain* (Vol. 145).

[4] Ozel, T. and Altan, T., 1998, May. Modeling of high speed machining processes for predicting tool forces, stresses and temperatures using fem simulations. In *Proceedings of the CIRP international workshop on modeling of machining operations* (pp. 225-234).

[5] Soo, S.L., Aspinwall, D.K. and Dewes, R.C., 2004. Three-dimensional finite element modelling of high-speed milling of Inconel 718. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *218*(11), pp.1555-1561.

[6] Constantin, C., Croitoru, S.M., Constantin, G. and Bisu, C.F., 2010, November. 3D FEM analysis of cutting processes. In *3rd WSEAS international conference on visualization, imaging and simulation* (pp. 41-46).

[7] Jin, X. and Altintas, Y., 2012. Prediction of micro-milling forces with finite element method. *Journal of Materials Processing Technology*, *212*(3), pp.542-552.

[8] Thepsonthi, T. and Özel, T., 2013. Experimental and finite element simulation based investigations on micro-milling Ti-6Al-4V titanium alloy: effects of cBN coating on tool wear. *Journal of Materials Processing Technology*, *213*(4), pp.532-542.