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Finite Element Modeling and Experimental Investigation of Micro Endmilling Forces on Aerospace Alloy

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Abstract

Miniaturization of products are gaining much more interest in scientific as well as in industrial sector because of its wide spread applications in many fields such as telecommunication, optics, biomedical and aerospace which necessitated the need to research and explores the possibilities of micro machining on special alloys. With the increased demand for micro components, the need for more accurate and precise micromachining process becomes necessary. Micro endmilling is one of the most promising micro machining process to fabricate complex miniaturized products. This paper presents a finite element model to predict the cutting force during micro endmilling process using ABAQUS/Explicit 6.18 by considering cutting edge radius effect, thermo-mechanical properties and failure parameters of the workpiece material on the basis of Johnson-Cook plasticity model. The meshing was done based on Arbitrary Lagrangian-Eulerian method. The force model was validated by experimental results using micromachining centre with a AlTiN coated WC micro endmill cutter of 500 µm effective diameter. Inconel 718, an aerospace alloy, was selected as the workpiece material because of its light weight, high corrosion resistance, high strength, etc. Responses such as cutting force and areal surface roughness (Sa) were also included in this paper to understand their variations with the process parameters. The predicted cutting forces are in good agreement with the experimental results. It was found that for feed per tooth less than the minimum uncut chip thickness cutting force deviates from the linear trend. The variation of areal surface roughness was found to be decreasing until feed per tooth reaches cutting edge radius and then there onwards areal surface roughness increases with feed per tooth.

Keywords: Micro endmilling, finite element modeling, cutting force, temperature, areal surface roughness, Inconel 718

1. INTRODUCTION

As the world is moving towards small size high strength components in various industries such as automation, medical, aerospace, etc. due to cost and weight reduction, the need for micro components is increased. This increased demand results in requirement of more precise and reliable micromachining process and advanced materials used. Among various micromachining processes micro end milling is one of the most promising fabrication process for miniature products because of its flexibility and ability to produce complex 3D parts. Micro end milling parts are relatively better in quality as compared to other products. But there are various problems associated with micro endmilling such as size effect, tool deflection, severe tool wear or tool breakage etc. The main reason for all the above problems is the high aspect ratio which results in high cutting force. In order to get a better quality product, detailed analysis of cutting force and surface roughness is very important. Inconel 718, a super alloy, is selected as a workpiece material because of its increasing application in aerospace, electronics and automobile industry because of its special properties like high strength, light in weight, high corrosion resistance, etc. However Inconel 718 is comes under difficult to machine material due to high hardness and low thermal conductivity. The abrasion properties and work hardening characteristic of Inconel 718 which lead to decreased tool life. The other difficulty in machining Inconel 718 is metallurgical damage to its surface due to high cutting temperature and pressure [1].

The characteristics of machining during micro and nano scale of non-ferrous alloys is analysed by Ng et al. [2]. The effect of specific cutting energy, friction coefficient and shear angle on chip geometry, cutting force and surface roughness is observed. The mechanistic model for cutting forces considering effect of run out, ploughing and elastic recovery is developed by Malekian et al.[3]. The elastic recovery effect is also considered during analysis by receptance coupling on tool tip. Oliveira et al. [4] proposed an experimental method to determine the size effect, specific cutting force and minimum uncut chip thickness in micromilling of dual phase carbon steel. From the detailed analysis of to understand the size effect and minimum uncut chip thickness in micro milling it was found that minimum chip thickness for micro milling varied from 1/3rd to 1/4th of cutting edge radius irrespective of workpiece material, tool geometry, method used for estimation of h_{min} and machining parameter. Srinivasa and Shunmugam [5] developed a mechanistic model considering basic principles of metal cutting and mechanical properties of materials for predicting cutting forces considering the material strengthening effect and edge radius effect for micro end-milling. Vogler et al. [6] introduced a micro endmilling cutting force model based on the minimum chip thickness concept to analyse the effect of cutting edge radius on cutting force.

Many researchers have also developed FEM model for predicting machining process for studying chip formation, tool wear, cutting temperature and cutting forces. Shi et al. [7] developed the FEM model for predicting the minimum chip thickness to increase the machining precision with the help of acoustic emission signals. The stress obtained by AE signal imples that material properties and tool geometry affects the minimum uncut thickness. Davoudinejad et al. [8] developed 3D Finite element model to predict the burr formation, chip flow and cutting forces in micro end milling of Al6061-T6. They also considered the effect of cutting edge radius and helix angle on chip formation and correlation of force profiles with burr dimension was also found. Lu et al. [11] developed a finite element model to predict the surface hardness during micro endmilling on Inconel 718 by using ABAQUS software. They used equivalent plastic strain to predict the micro hardness and found that surface micro hardness increases first and then decreases due to size effect.

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In this paper, 2D Finite element model for the prediction of cutting force, stress and temperature developed during micro endmilling of Inconel 718 by considering the effects of rake angle, cutting edge radius, thermo mechanical and failure properties of the workpiece material on the basis of Johnson-Cook plasticity model is proposed. Experimental cutting force results were verified with the proposed FE model. A detailed analysis of the cutting force and areal surface roughness were carried out and overall conclusions were reported.

2. EXPERIMENTAL WORK

2.1 Work piece material

Inconel 718 is used as the work piece material for this work because of its superior properties like high hardness, high strength to weight ratio, resistance to high temperature loading, resistance to corrosion. Table 1 shows the physical properties.

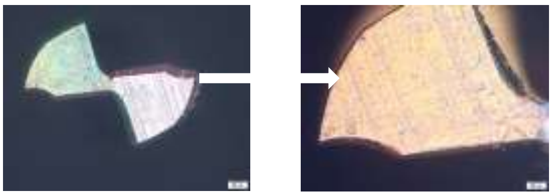
Table 1

Properties of Inconel 718

Mechanical Properties	Inconel 718
Density (kg/m^3)	8200
Thermal conductivity (W/mK)	6.5
Young's modulus (GPa)	210
Vickers hardness	350
Yield strength (MPa)	915
Melting temperature (˚C)	1225

2.2. Cutting tool

AlTiN coated WC endmill with 500 µm cutter diameter, 8^0 rake angle and 10^0 clearance angles were used for this study. Since cutting edge radius has a significant influence on size effect in micromachining, it has been measured physically using optical microscope. Edge radius was measured in the range of 3µm.



(a) (b)

Fig. 1. Optical images of (a) Micro endmill cutter (b) Cutting edge

2.3. Experimental set up

Experiments were conducted by using micro machining centre (DT110, Mikrotools, Singapore) with AlTiN coated WC micro end mill tool with an effective diameter of 500 µm. Micro channels of 10 mm length were machined on Inconel 718 work piece to validate the FE model and to analyse the effect of feed per tooth on cutting force and areal surface roughness.

Fig. 2. Experimental set up

KISTLER mini dynamometer (9256C2) was used to measure the cutting force. Inconel 718 sheet was directly mounted on to the dynamometer. The configuration of experimental set up for measuring cutting force during micro endmilling is shown in the Fig. 2. Areal surface roughness (Sa) was measured by using 3D non-contact optical profiler (Alicona Infinite focus G5). Table 2 shows the experimental plan.

Table 2

Experimental plan

Machine tool	Micro machining centre (DT110, Mikrotools, Singapore)
Cutting speed (m/min)	7.85
Depth of cut (mm)	0.1
Feed per tooth (µm)	0.1, 0.5, 0.9, 1.3, 2, 3, 4, 5
Cutting tool	AlTiN Coated WC end mill cutter with 500 µm cutter diameter
Workpiece material	Inconel 718
Dynamometer	KISTLER 9256C2
3D Optical profiler	Alicona Infinite Focus G5

3. FINITE ELEMENT SIMULATION OF MICRO ENDMILLING ON INCONEL 718

ABAQUS/Explicit 6.18 was used for orthogonal FE simulation of the micro endmilling of Inconel 718 based on plane strain. Coupled thermo mechanical analysis was used to include thermal effects. The element type used for this analysis is CPE4RT. The cutting tool in simulation is set as rigid body so as to reduce the computation time and a reference point (RP) used to acquire the data value. The coefficient of friction has been taken as 0.4 for the simulation purpose. The mesh size selected for this simulation is lower than the cutting edge radius in order to ensure the accuracy during simulation. The workpiece restricted in all direction and the tool is moving with a uniform cutting velocity in Y direction as shown in Fig.3.

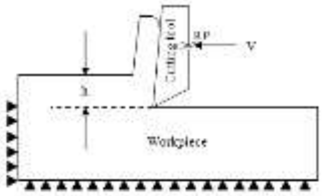


Fig. 3. FE model of micro end milling

Johnson-Cook (J-C) constitutive model [10] is adopted to describe the workpiece material behavior of Inconel 718.

$$\bar{\sigma}_{JC} = [A + B(\epsilon)^n] \text{x} \left[1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \text{x} \left[1 - \left(\frac{T-T_0}{T_m-T_0}\right)\right] \quad (1)$$

Where $\bar{\sigma}_{JC}$ is the flow stress, ε is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, and $\dot{\varepsilon}_0$ is the reference plastic strain rate, always $\dot{\varepsilon}_0$=1.0/s , T is the cutting temperature, T_m melting temperature and T_o is room temperature. n and m are the strain hardening index and thermal softening index respectively. A, B and C are J-C Parameters represent the yield strength, strain and strain rate sensitivities of the material. Table 3 shows the J-C parameters for Inconel 718.

Table 3

Johnson-Cook model parameters for Inconel 718 [11]

A (MPa)	B (MPa)	C	n	m
450	1700	0.017	0.65	1.3

Eq.2. shows the Johnson-Cook failure model used for damage initiation.

$$\epsilon_{failure} = \left[d_1 + d_2 \exp\left(d_3 \frac{P}{\bar{\sigma}_{JC}}\right)\right] \text{x} \left[1 + d_4 ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)\right] \text{x} \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)\right] \quad (2)$$

J-C failure parameters for Inconel 718 are shown in Table 4

Table 4

Johnson-Cook failure parameters for Inconel 718 [11]

d_1	d_2	d_3	d_4	d_5
-0.239	0.456	0.3	0.07	2.5

The uncut chip thickness (h) in micro endmilling process varies with cutter rotation angle (θ) and feed per tooth (f_t) as shown in equation (3). Simulations were run for different feed per tooth by taking h= f_t.

$$h = f_t \text{ Sin}(\theta) \quad (3)$$

4. RESULTS AND DISCUSSION

4.1 Finite element simulation results

Fig.4 (a) shows the FE simulation results of von-Mises stress distribution using ABAQUS/Explicit 6.18 using dynamic, explicit, adiabatic conditions. Maximum simulated von-Mises stress occurred in the shear zone is 1785 MPa, which is in the tool chip interphase and shear zone. This is due to higher value of force required at the cutting edge in the shear zone for chip formation. However, the increase of stress value may be due to the size effect of the micro-milling process.

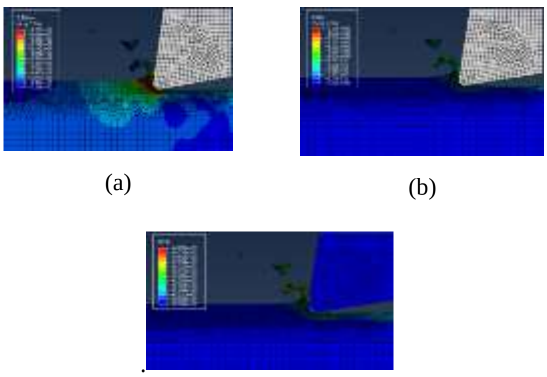


Fig. 4. Simulated (a) von-Mises stress distribution (b) PEEQ and (c) temperature distribution at a cutting speed of 15.7 m/min, feed rate of 3µm/tooth and depth of cut of 0.1 mm

The equivalent plastic strain (PEEQ) is used to describe the surface residual strain shown in Fig. 4(b). Microhardness prediction can be predicted based on the PEEQ simulation results [12]. From Fig. 4(c) the maximum value of simulated temperature is 499 ^{0}C. This temperature value is in the range of the temperature generated during micro-milling of Inconel 718

4.2 Cutting force

For acquiring the force signal during micro end milling process, KISTLER mini dynamometer (9256C2) was attached to the micromachining centre DT110 in such a way that force components F_X, F_Y and F_Z were measured as shown in Fig. 5. The RMS value of force has been used for experimental cutting force for model validation.

In end milling process, orthogonal thrust force (F_t) will be radial force (F_{rad}) and orthogonal cutting force (F_c) will have two components, the longitudinal force F_{lon} and the tangential force F_{tan} shown in the Equation 4 and Equation 5. [6]

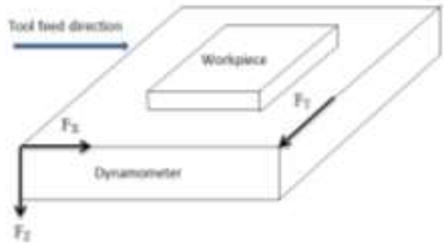


Fig. 5. Cutting force direction

$$F_{lon} = F_c \sin\psi \quad (4)$$

$$F_{tan} = F_c \cos\psi \quad (5)$$

In order to relate these forces to the force acquired from the Kistler dynamometer, we need to transform F_t (or F_{rad}), F_{lon} and F_{tan} to Cartesian coordinate system. For any angular position θ of the cutting tool, end milling forces can be resolved into Cartesian coordinate as given below from the Fig.6.

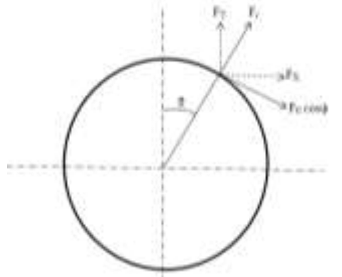


Fig. 6. Transformation of end milling forces to Cartesian coordinate system

$$F_x = F_r \sin\theta + F_c \cos\psi \cos\theta \quad (6)$$

$$F_y = F_r \cos\theta - F_c \cos\psi \sin\theta \quad (7)$$

Fig. 7 shows the variation of cutting force with feed per tooth for both simulation and experimentation. The cutting force simulations were done for four different feed per tooth. The simulated cutting force shows a good agreement with experimental cutting force results. Variation in the simulated and experimental cutting force values were observed because of 2D simulation and tool wear and material microstructure affects were not considered in this FE model. In actual case the tool wear, tool geometry and material microstructure plays an important role. Detailed experimental investigations to understand the size effect in micro endmilling were performed by giving equal importance to size effect and outside size effect region. From the Fig.7 it can also be observed that above 1µm feed per tooth cutting force increases almost linearly with feed per tooth and below 1µm feed per tooth cutting force deviates from the linear trend. Reason for this could be due to the fact that 1µm falls in the range of minimum uncut chip thickness(MUCT) for the tool used in this study (cutting edge radius of the tool was approximately 3µm). MUCT is to be in the range of 1/3rd to 1/4th of cutting edge radius [4]. When feed per tooth becomes less than MUCT ploughing (within the size effect region) is dominated. This is the reason for the increase in cutting force value at lower feed per tooth. When feed per tooth is much higher than MUCT (outside size effect region) shearing mechanism is dominant like conventional machining.

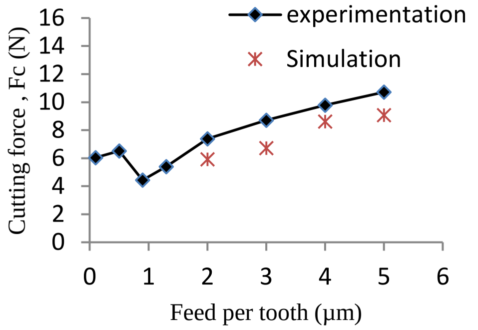


Fig. 7. Variation of feed per tooth with cutting force for cutting speed of 7.85m/min and 0.1mm depth of cut

4.3 Areal surface roughness

Areal surface roughness (Sa) was measured by using 3D non-contact optical profiler (Alicona Infinite focus G5). Fig.8 shows the variation of feed per tooth with areal surface roughness. It can be observed that initially as feed per tooth increases areal surface roughness decreases and reaches a minimum value and then increases as feed per tooth increases. This is mainly due to size effect. Feed per tooth less than minimum uncut chip thickness, this is in the ranges of 1/3rd to 1/4th of cutting edge radius [4], results in ploughing. So for feed per tooth less than minimum uncut chip thickness areal surface roughness reduces with feed per tooth up to minimum chip thickness range. Outside size effect region areal surface roughness increases as in the case of macro machining.

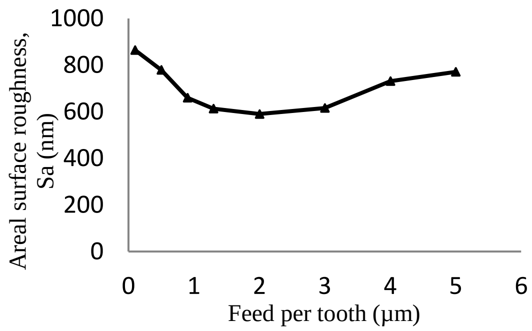


Fig. 8. Variation of areal surface roughness with feed per tooth for cutting speed of 7.85m/min and 0.1mm depth of cut

5. CONCLUSIONS

In this paper a 2D finite element modeling of cutting force during micro-end milling of Inconel 718 using ABAQUS/Explicit 6.18 is described. This finite element model is able to explain cutting force, von-Mises stress distribution, equivalent plastic strain (PEEQ) distribution and workpiece temperature distribution during micro endmilling under different cutting conditions by considering the effects of cutting edge radius, cutting speed, chip thickness and feed rate. Maximum value of Von-Mises stress observed to be more than those of macro milling of Inconel 718. This is due to fact that effect of cutting edge radius of the tool and low feed rates were applied in micro milling. The simulated cutting forces results were successfully validated with experimental values. The experimental investigation of cutting forces showed the size effect in micro endmilling process clearly (Fig.7). Due to size effect within the size effect region the cutting force shows a nonlinear trend unlike to macro machining. It was found that while machining within the size effect region, areal surface roughness decreases with feed per tooth. Whereas above size effect zone, areal surface roughness increases with feed per tooth as in the case of macro machining.

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