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Deformation of thin parts in micromilling

Ismail Lazoglu (2)*, Ali Mamedov

Manufacturing and Automation Research Center, Koc University, Istanbul 34450, Turkey

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ABSTRACT

Deformation is one of the major problems in the micromilling of thin parts. Deformation of thin parts is mainly due to the machining induced residual stresses remained in the part and directly affects the dimensions and form tolerances of microparts. Therefore, this article proposes a new modeling approach to predict deformation of thin parts in micromachining. In the modeling approach, micromilling induced mechanical and thermal loads on the workpiece are estimated, and a new multi-physics based finite element modeling (FEM) approach is proposed to predict thin part deformation in micromilling for the first time. The newly developed deformation model is validated under various cutting conditions in the micromilling of Ti–6Al–4V.

1. Introduction

Micromilling is a widely used micromachining process for the production of miniature parts in various industries such as biomedical, aerospace, and optics. Nowadays, there is a substantial increase in demands for miniature parts with tight tolerances in the industry. Plastic deformations are one of the major concerns while manufacturing microparts with thin walls. Due to this reason, production of high quality miniature parts with tight tolerances still requires more precise modeling and deeper understanding of the micromachining processes.

Due to shearing, friction and ploughing mechanisms, machining forces and thermal loads always exist in the mechanical micromilling process, and these loads may significantly affect the plastic deformation in thin parts. For this reason modeling of thin part deformation is still a scientific challenge in machining community.

A significant amount of research has been dedicated to modeling of cutting forces, temperature, residual stresses and surface integrity that affect machining-induced deformations. Jawahir et al. [1] published a comprehensive work on recent progress in experimental and theoretical investigations of surface integrity and residual stresses. Denkena et al. [2] investigated the effects of cutting parameters and cutting edge geometry on residual stresses and subsurface material changes in Aluminum alloys. Lazoglu et al. [3] developed an analytical elastoplastic model to estimate machining induced residual stresses in orthogonal machining and validated their model via X-ray diffraction residual stress measurements on Waspaloy material. And later, Mamedov et al. [4] modeled cutting forces in micro-milling and studied deflection of the microend mill. Fergani et al. [5] introduced an analytical technique to predict the residual stress induced distortions in micromilling of Al7050 thin plates. Lazoglu et al. [6,7] proposed a steady-state temperature model, and a model to predict the 3D transient temperature model in oblique machining using finite difference methods. Brinksmeir and Sölter proposed a method to predict the shape deviation for large parts such as ground linear rail guides and turned bearing rings [8]. Smith et al. [9] introduced a process that uses sacrificial structures for thin part machining to avoid insufficient static and dynamic stiffness of parts.

Although there are significant contributions to the macro-scale machining modeling, there is no accurate model of plastic deformation in the micromilling of thin parts in the literature yet. Therefore, this article presents a new multi-physics based finite element modeling (FEM) approach for the micromilling-induced plastic deformation of thin parts. The effects of the cutting parameters, forces and workpiece temperatures are analyzed in the proposed model. The accuracy of the model is demonstrated by force and laser displacement measurements in real time during micromilling of Ti–6Al–4V under various cutting conditions and offline thin part plastic deformation measurements with the white light interferometer (WLI).

2. Modeling of micromilling induced plastic deformation

The material used in the experiments, Ti–6Al–4V, is a commonly used engineering material employed in biomedical systems and implants. Titanium alloys are known as difficult to machine materials due to their thermo-mechanical properties, thus Ti–6Al–4V is interesting to investigate material. In order to develop a model that simulates micromilling induced deformations, it is critical to have a precise mechanic and thermal model of the cutting process. These models have been developed by the authors and details can be found in [4,10]. Briefly, a comprehensive analytical model of microcutting process by considering the tool edge radius effect and tool run-out was developed to estimate

* Corresponding author. Tel.: +90 2123381587; fax: +90 2123381548.
E-mail address: ilazoglu@ku.edu.tr (I. Lazoglu).

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cutting forces and cutter deflection during microend milling [4]. Estimated cutting forces are presented as the function of cutting coefficients in both shearing and ploughing zones. Ploughing force is modeled as the function of ploughed area and related to the height of elastically recovered material. The total differential cutting forces, including shearing and ploughing forces, are estimated as the following:

$$\begin{bmatrix} dF_x \\ dF_y \\ dF_z \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \left(\begin{bmatrix} K_{tc}h_\theta dz \\ K_{rc}h_\theta dz \\ K_{ac}h_\theta dz \end{bmatrix} + \begin{bmatrix} K_{te}dz \\ K_{re}dz \\ K_{ae}dz \end{bmatrix} + \begin{bmatrix} K_{tp}A_p dz \\ K_{rp}A_p dz \\ K_{ap}A_p dz \end{bmatrix} \right) \quad (1)$$

Here, dF_x, dF_y and dF_z represent differential feed (x), cross feed (y) and longitudinal (z) forces, θ stands for the tool immersion (rotation) angle, K_{tc}, K_{rc} and K_{ac} are the cutting coefficients, K_{te}, K_{re} and K_{ae} are the edge coefficients, K_{tp}, K_{rp} and K_{ap} are the ploughing coefficients, A_p denotes the ploughing area, dz denotes the differential axial depth of cut and h_θ stands for uncut chip thickness. The total cutting forces are determined by integrating the differential forces [4].

The temperature fields are calculated by the hybrid analytical and finite element temperature model [10], where shearing and frictional heat formed during cutting is calculated from Eqs. (2) and (3) as follows:

$$P_s(\theta) = V_s \cdot F_s(\theta) = \frac{V \cdot \tau_s \cdot a \cdot h(\theta) \cdot \cos(\alpha_n)}{\cos(\phi_n - \alpha_n) \cdot \sin(\phi_c)} \quad (2)$$

$$P_f(\theta) = V_c \cdot F_u(\theta) = \frac{V \cdot F_R(\theta) \cdot \sin(\phi_n) \cdot \sin(\beta_a)}{\cos(\phi_n - \alpha_n)} \quad (3)$$

where P_s, P_f, V_s, V_c, V, F_s, F_u, F_R, τ_s, h, a, α_n, β_a, ϕ_n, ϕ_c and θ represent the shearing power, the friction power, the shear velocity, the chip velocity, the cutting velocity, the shear force on shear plane, the friction force on the rake face, the planar resultant cutting force, the average shear flow stress, the uncut chip thickness, the depth of cut, the normal rake angle, the friction angle, the normal shear angle, the shear angle and the immersion angle, respectively. Later analytically calculated shearing and frictional heat are applied to shear plane and tool–chip interface and temperature distribution on the tool and the workpiece is calculated. The cutting process is simulated as time-dependent heat transfer problem in a multi-physics based FE software. Instantaneous tool and workpiece temperatures are simulated for micromilling process [10].

2.1. Deformation modeling of microend milling process

A finite element model for simulation of deformations was developed using a multi-physics approach. A combined effect of cutting forces acting on the thin part and temperature fields on the workpiece generated during cutting is applied to the thin part as an input for the simulation of deformation. The process is simulated as a time-dependent multi-physics problem consisting of structural mechanics and heat transfer. The elastoplastic material model with isotropic tangent modulus is employed in deformation simulations.

The part is loaded with moving heat source and mechanical load at each axial depth of cut for a time period equal to the machining time. Later, thermal and mechanical loads were removed and the thin part undergoes elastic recovery, as the result total plastic deformation after micromilling. In the presented micromilling cases, cutting was full immersion slot milling, the length of the workpiece along the feed direction was 10 mm, the total depth of cut (H) is 2 mm and thickness of the machined thin wall (t) was 100 μm. At each axial depth of cut, the workpiece temperature calculated from the thermal model was applied to the part in cutting region via moving heat source. Meanwhile, the cutting forces acting on the thin part were determined from the micromilling mechanic model and applied to the part as an equivalent force (F_{eq}). The mesh element type is selected as free triangular. The minimum and maximum mesh sizes were 3 μm and 80 μm, respectively. The geometry of the thin part and FE model are presented below in Fig. 1. Tool and workpiece properties and the cutting conditions are given in Tables 1 and 2.

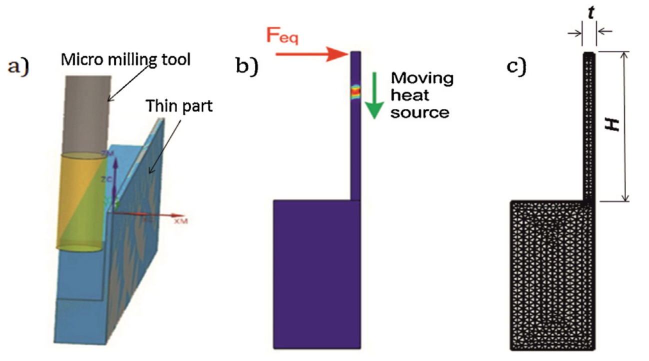

Fig. 1. (a) CAM model of the workpiece, (b) FE model of deformation simulations, (c) Mesh strategy of the FE model.

Table 1
Tool and workpiece properties.

Tool diameter	800 μm
Rake angle	8°
Edge radius of the tool	6 μm
Density of Ti–6Al–4V	4430 kg/m³
Shear stress of Ti–6Al–4V	613 MPa
Young's modulus of Ti–6Al–4V	110 GPa
Poisson's ratio	0.34
The initial yield stress of Ti–6Al–4V	880 MPa
Isotropic tangent modulus of Ti–6Al–4V	1.25 GPa

Table 2
Cutting conditions for deformation simulations and cutting experiments.

Case	Cutting speed [m/min]	Spindle speed [rpm]	Axial depth of cut [μm]	Feedrate [mm/min]	Feed per tooth [μm/tooth]	The temperature of the workpiece at the tool exit [°C]
1	25	10 000	50	100	5	60
2	25	10 000	50	200	10	88
3	25	10 000	100	100	5	85
4	25	10 000	100	200	10	106
5	25	10 000	150	100	5	90
6	25	10 000	150	200	10	123
7	50	20 000	50	200	5	72
8	50	20 000	50	400	10	108
9	50	20 000	100	200	5	110
10	50	20 000	100	400	10	140
11	50	20 000	150	200	5	120
12	50	20 000	150	400	10	167

The convective air cooling is applied to the outer surface of the workpiece, the heat transfer coefficient for the stationary workpiece is h_w = 10 W/m² K. Temperature-dependent thermo-physical properties of Ti–6Al–4V material were implemented. The temperature distribution in the workpiece is calculated according to the time-dependent heat transfer equation in solid bodies, given in Eq. (4).

$$\rho c_p \frac{\partial T}{\partial t} + k \nabla T = Q \quad (4)$$

where Q and ∇T are heat source and temperature gradient, ρ, k and c_p are the material density, the temperature-dependent thermal conductivity and the heat capacity. Later, temperature coupling is used to add temperature distribution calculated in the heat transfer module as an input to the solid mechanics module. At the same time thermal expansion is added to the model under the linear elastoplastic material and calculated from Eq. (5):

$$\epsilon_{th} = \alpha \Delta T \quad (5)$$