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Original Article

3D SPH-FEM modelling of micro milling of Ti-6Al-4V

Murat DEMİRAL, Ali MAMEDOV*

College of Engineering and Technology, American University of the Middle East, Kuwait

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ABSTRACT

Modelling of micro milling process is still one of the most challenging research topics. This paper presents a new 3D SPH-FEM technique used to model micro end milling operation of titanium alloy. Titanium alloys are known as difficult to machine materials because of their thermo-mechanical properties. The low thermal conductivity of these alloys results in high thermal loads on cutting tool during machining process, which results in excessive tool wear that affects final part accuracy. Due to this reason accurate modelling of the process is essential. The finite element modelling techniques previously presented in the literature encountered several characteristic problems, such as the negative volume and/or mesh distortion. In this paper the smoothed particle hydrodynamics (SPH) technique, a mesh-free method, has been efficaciously utilized to overcome these complications. Presented model is validated through comparison of estimated and experimentally measured cutting forces.

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INTRODUCTION

The technological progress has allowed manufacturing of high-quality micro parts with complex free form geometry within desirable tolerances. Micro milling is extensively used in manufacturing processes for production of miniature sized parts for innovative technologies like micro sensors, biomedical parts, micro dies and molds, etc. Production of miniature sized parts requires manufacturing with tight tolerances. Due to this reason accuracy of the process is vital. Since, cutting force and temperature are key factors affecting tool wear, accuracy of the process is affected by temperature as well as by the mechanical effects.

Several groups of researchers worked on modeling of the micro milling process. Different techniques were used to estimate cutting forces, cutting temperature, tool wear and final part accuracy. Thepsonthi and Ozel [1, 2] investigated the effect of tool helix, tool edge radius and burr formation using 3-D finite element simulation of micro-milling, compared viscoplastic and elasto-viscoplastic models and by employing this simulation technique aimed to optimize high performance micro milling. Molinari et al. [3] presented a comprehensive FEM analysis of contact problem, which investigates contact variables and thermal effects at the tool chip interface. Mamedov and Lazoglu [4] presented a hybrid thermo-mechanical and FE model of the micro milling process, where heat formed in primary and secondary cutting zones is estimated using analytical thermo-mechanical model and temperature distribution in the tool and workpiece is estimated using time-dependent FE heat transfer model. Budak et al. [5]

***Corresponding author.**
*E-mail address: ali.mamedov@aum.edu.kw

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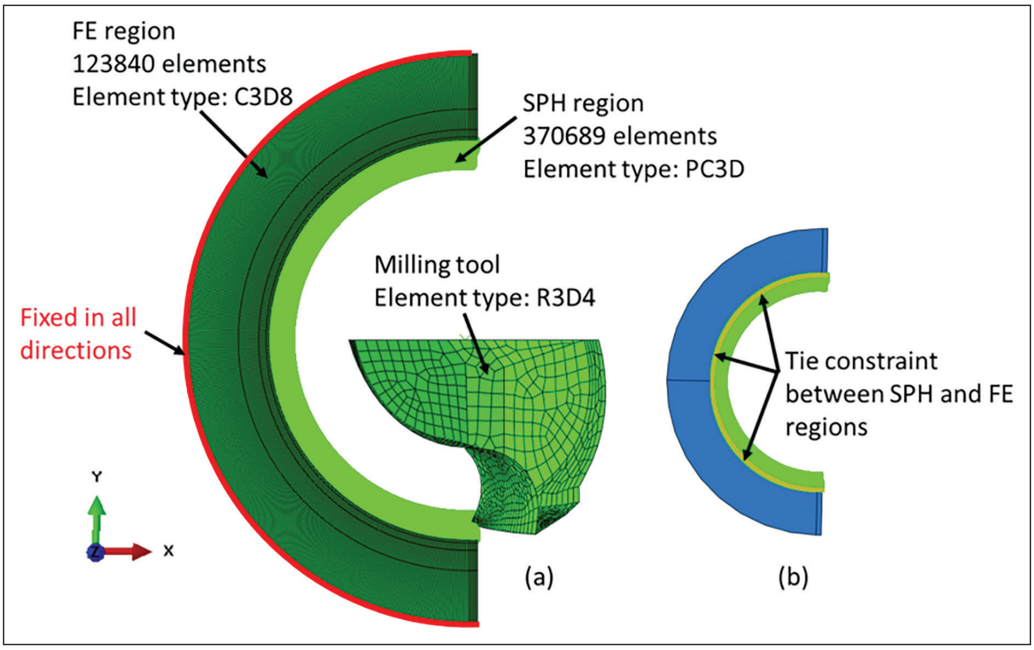

Figure 1. **(a)** 3D SPH-FE model of micro-milling of Ti alloy **(b)** Details of tie constraint imposed.

presented a thermo-mechanical model of the third deformation zone during micro end milling process to estimate cutting forces. Presented model eliminates the need for extensive number of calibration tests for identification of edge coefficients and edge forces.

Here in this paper, a new 3D SPH-FEM modelling of micro end milling operation is presented. In this model the smoothed particle hydrodynamics (SPH) technique is effectively used to overcome typical encountered problems of FEM modeling of cutting processes, such as mesh distortion and negative volume. The presented model is validated through comparison of the estimated cutting force results with experimental results previously published by the author and available in the literature.

SIMULATION PROCEDURE

In metal cutting process, the deformation is highly concentrated in a small zone, where, as a result, the chip is formed. Simulation of this process can be performed using the Finite Element Method (FEM). However, the negative volume and/or mesh distortion are characteristic problems encountered, especially when fracture is involved in the simulations. This can be avoided by introducing an element deletion criterion, where the distorted elements are deactivated in the model based on a predefined failure criteria such as stress, strain, damage, etc. On the other hand, the smoothed particle hydrodynamics (SPH) technique, a mesh-free method, has been efficaciously utilized to simulate the fracture of solids. In this method, the problem domain is divided into a set of randomly or uniformly distributed particles. However, the computational time for SPH elements is more than that of FE simulations [6]. To lessen the overall simulation time, the number of SPH particles in the model needs to be used only in the regions where the fracture occurs [7]. Therefore, the SPH and FEM were coupled in this study.

Figure 1a shows the details of developed 3D hybrid SPH-FE model of micro milling of titanium alloy Ti-6Al-4V using adiabatic Abaqus/Explicit module. To compromise the accuracy of the solutions and computational time, the distance between SPH particles kept closer while the mesh in the remaining area was set to sparse. That resulted in 370689 particles with an element type of PC3D in the SPH region and 123840 hexagonal elements with an element type of C3D8R in FE region. The meshless and meshed regions were connected to each other by a tie constraint (Fig. 1b). The inner and outer diameter of the workpiece are 800 μm and 1200 μm, respectively, with its height is 150 μm. Depth of cut is 100 μm and spindle speed is 10,000 rpm. The initial temperature of the workpiece is set to 25°C. As the cutting tool is more rigid than the workpiece material, it is modelled as a rigid body with an element type of R3D4. 800 μm diameter two fluted Tungsten Carbide micro end mill with 25.2° helix angle and 6 μm edge radius was used in simulations and validation experiments.

Interaction between cutting tool and workpiece is handled with the general contact in Abaqus/Explicit. The Coulomb's friction law with μ (coefficient of friction) equals to 0.5 is defined for the tangential behavior between the contact surfaces [8], while a hard contact pressure overclosure property is considered for the normal behavior.

Table 1. Physical properties and material constants of Ti6Al4V [10]

Physical/ elastic properties	Density [kg/m³]	Elastic modulus [GPa]/ Poisson's ratio	Thermal conductivity [W/mK]	Linear thermal expansion [10^{-6}/°C]	Specific heat [J/g°C]
	4430	110/0.33	7.2	8.7	0.5263
Johnson–cook constants	*A*	*B*	*C*	*n*	*m*
	862	331	0.012	0.34	0.8

Johnson–Cook material law [9] is used to simulate the behavior of Ti-6Al-4V subjected to micro-milling process. This material law is commonly adopted for the dynamic problems characterized by high strains, strain rates and temperature effects. In the simulations 90% of the plastic strain energy is considered to be dissipated as heat owing to localized adiabatic heating. Its physical, thermal and elastic properties as well as five parameters of Johnson-Cook constitutive equation (A, B, C, n, and m) are listed in Table 1.

In the next, the basics of SPH theory are summarized briefly. In this method, the conservation laws of continuum fluid dynamics are transformed into integral equations using an interpolation function. The kernel approximation of a function is integrated over the computational domain, where it is obtained at a certain position by using the smoothing kernels W as follows:

$$f(x_i) = \int_{\Omega} f(x_j)W(x_i - x_j, h)dy \quad (1)$$

where x_j denotes the material positions in the compactly supported domain and h is the smoothing length changing spatially and temporally. In the description of W, the cubic-spline integral approximation is most commonly used (Fig. 3), where the next requirements are to be fulfilled:

$$\int_{\Omega} W(x_i - x_j, h)dx_j = 1$$

$$\lim_{h \to 0} W(x_i - x_j, h) = \delta(x_i - x_j) \quad (2)$$

$$W(x_i - x_j, h) = 0, \text{ when } |x_i - x_j| > kh$$

Here, the Dirac delta function $\delta(x_i)$ is obtained when smoothing length approaches zero. k represents the constant as the relative distance between points x_i and x_j.

In SPH method, the solution domain is usually discretized into homogeneously distributed particles having the field variables, where they are driven by pressure gradient and viscous stress in the flow field. The discrete form of the field variable at a particle is written as follows:

$$f(x_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j)W(x_i - x_j, h) \quad (3)$$

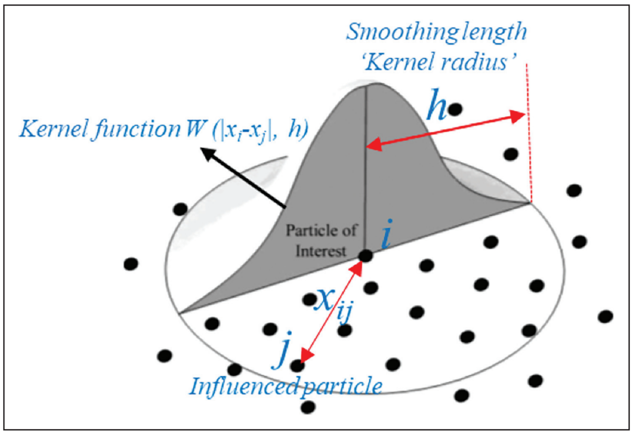

Figure 2. Example of a smoothing function (kernel).

where the subscript i denotes the concerned particle, j denotes the particle within the supported domain of particle i, N is the number of nearest particles, m_j and ρ_j are the mass and density for each of them, respectively. The number of adjacent particles is obtained based on the smoothing length. More information about SPH method can be found in [11].

RESULTS AND DISCUSSION

Simulation is validated through comparison of estimated planar resultant force with and experimentally measured cutting force and analytically estimated cutting force calculated by mechanistic cutting force model for micro milling process proposed by Mamedov et al. [12]. For validation of the proposed model authors used experimental results previously presented by Mamedov and Lazoglu [4]. Cutting experiments were performed on Ti-6Al-4V titanium alloy at 10.000 rpm spindle speed, using 800 µm diameter two fluted Tungsten Carbide micro end mill. To compare estimated and experimentally measured cutting forces planar resultant force was calculated. As shown in Figure 3, planar resultant force estimated with proposed 3D SPH-FEM model has good correlation with experimentally measured and analytically simulated force. Planar resultant force estimated with proposed model is 10.1 N, experimentally measured planar resultant force is 10.5 N and analytically calculated planar resultant force is 9.4 N. It should be emphasized that the fluctuations in the estimated cutting

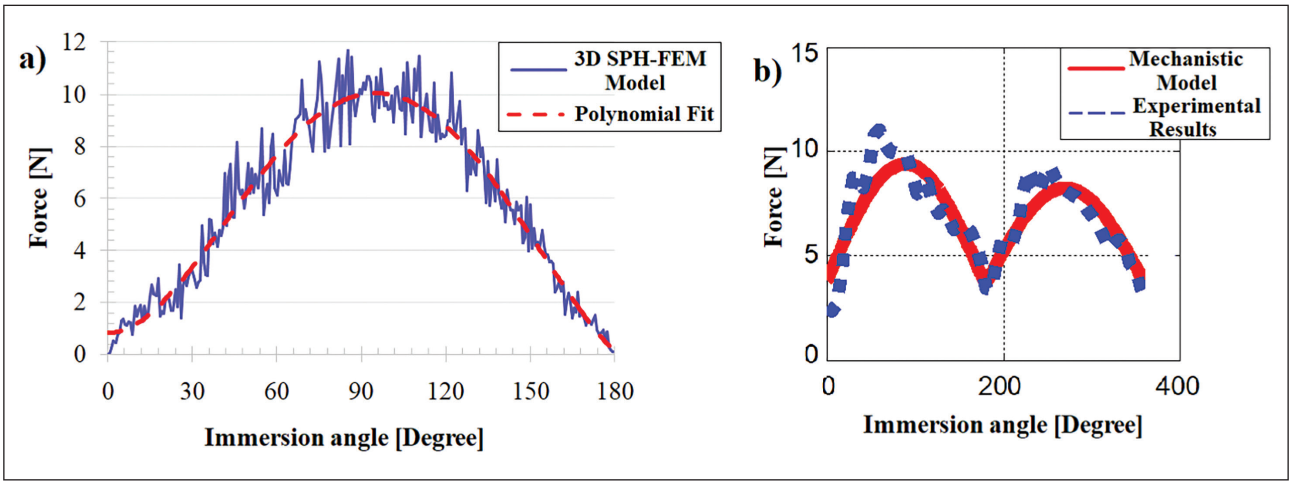

Figure 3. **(a)** Planar resultant force simulated with proposed 3D SPH-FEM model, **(b)** Experimentally measured and analytically calculated planar resultant force [depth of cut 100μm and feedrate 10 μm/rev-tooth].

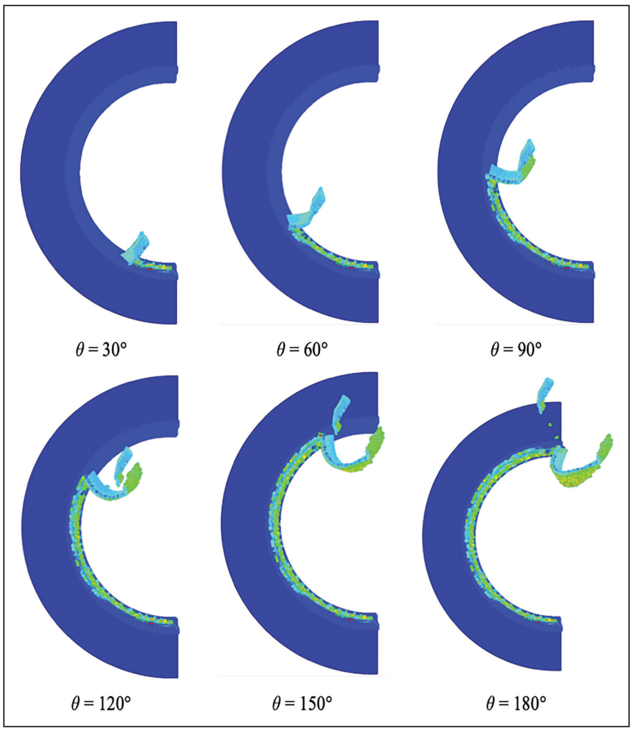

Figure 4. Simulation of the chip formation during micro end-milling process according to immersion angle.

force occurred due to two major reasons: (1) a small stable time increment used in analysis, where dynamic response associated with stress waves moving through the material (and reflecting at boundaries) were captured in the overall cutting force response; (2) reorientation of the local mesh during cutting process leading to a variation in the shear angle [13].

Additionally, simulation of the chip formation during micro end-milling process according to immersion angle is presented in Figure 4.

CONCLUSION

Different from the previously presented papers, this paper presented a new 3D hybrid SPH-FE model of micro milling process able to predict cutting forces. The developed model uses smoothed particle hydrodynamics (SPH) technique, a mesh-free method, to overcome common complications that occur during FE modelling of cutting processes. Proposed model was validated through comparison of estimated planar resulted cutting forces with experimentally measured forces previously presented by author and available in literature. Results showed that simulated and experimental cutting forces are in a good agreement. As further development, authors aim to validate thermal aspect of the proposed model and estimate temperature distribution fields generated during micro milling process.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Murat Demiral: Methodology, investigation, analysis.

Ali Mamedov: Conceptualization, original draft, validation.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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