SPH Modelling of Cutting Forces while Turning of Ti6Al4V Alloy

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1 Abstract

A growing interest in modelling and simulation of machining processes has been witnessed in the past few decades. Smoothed particles hydrodynamics (SPH), one of the latest and developing methods used for that purpose, is a powerful technique that can be efficient in handling problems in which large deformation occurs. The current work aims to present and evaluate the use of SPH in modelling the machining processes. A coupled thermo-mechanical analysis of a 3D model is performed using LS-DYNA to predict the cutting forces during face turning of Ti6Al4V alloy, at different cutting speeds. The Johnson-Cook material constitutive model is used along with both linear polynomial and Gruneisen equations of state in order to accurately simulate the material behavior and investigate their effects on the results. The simulation results are validated using a previously published experimental work.

2 Introduction

Titanium and its alloys are used in wide and diverse applications where reliability, high strength at extreme temperatures, fracture resistance and high strength-to-weight ratio are required such as biomedical applications as well as in aerospace and automotive industries, chemical plants, power generation, oil and gas extraction, sports, and other major industries. The machinability of titanium alloys is considered poor because of their high strength, low thermal conductivity and low modulus of elasticity. Therefore, machining titanium alloys result in high cutting temperatures, high forces, chatter and tool wear [1].

There has been a growing interest in using finite element (F.E.) methods in modelling of machining processes. The common approaches that have been used for that purpose are Lagranian, Eulerian and Arbitrary Largrangian-Eulerian (A.L.E.). In the Eulerian approach, the mesh is fixed in the space and the large distortions can be handled without the need to define a failure criterion. However, this approach assumes a steady state mesh configuration and, therefore, the chip morphology has to be known before the simulation. Furthermore, this approach is not well suited for applications that need monitoring the material properties in fixed volumes. It is widely used in fluid dynamics. In the Lagrangian approach, the mesh is deforming in time with the material and a pre-defined failure surface or line and failure criterion have to be defined. This approach is mainly used in structural mechanics. However, this approach is not able to follow large distortions of the computational domain. To overcome such struggle, a very fine mesh is required where high deformation occurs to avoid mesh distortion problems that can terminate the simulations. The A.L.E. method was established to overcome the shortcomings of purely Lagrangian and purely Eulerian approaches. The distortions of the mesh that can be handled by A.L.E is greater than that allowed by a purely Lagrangian method. The combination between Eurlerian and Lagrangian approaches received much research interest and achieved a lot in obtaining more stable solutions. Another advanced technique for the Lagrangian approach used in DEFORM software, called remeshing-rezoning, by which the element is deleted with all its parameters once it reaches the pre-defined critical damage value, and then new elements are added to smooth the rough boundary produced by element deletion [2]. However, it is difficult to use grid-based numerical methods in order to solve problems where large deformations, moving material interfaces, deformable boundaries and free surfaces, exist.

Recently, the mesh-free methods could overcome the struggles of finite element techniques by avoiding the mesh distortion problems, and the need to remeshing and defining failure criterion. Consequently, these methods can be employed in large deformation problems such as blast, bird strike, machining problems and in applications where discontinuities can exist such as crack propagation problems. The most common mesh-free method is Smoothed Particles Hydrodynamics (SPH). However, in order to use these methods, high CPU and memory are required [3].

The SPH, a developing explicit mesh-free Lagrangian method, was employed in metal cutting simulations in a report published by Heistein in 1997 [4]. The method was developed by Gingold and Monaghan [5] and Lucy [6] to be used in astrophysics. SPH was then used for fluid flow problems governed by Navier-Stokes equations. In 1991 Libersky and Petschek extended the use of SPH to solid mechanics [7]. A detailed review on the use of SPH on solid mechanics problems can be found in [3].

For the modelling of machining processes, Limido et al. [8] developed a 2D cutting model using SPH method for both the workpiece and the tool. Villumsen et al. [9] developed a 3D orthogonal cutting model for Al 6082-T6 alloy in which a traditional finite element is used for the tool, and SPH is used for the workpiece. The study investigated the effect of SPH particles resolution, mass scaling, time scaling, and coefficient of friction on both cutting and thrust force components. However, the author did not take the thermal parameters of the workpiece material during simulations. Espinosa et al. [10] developed a 3D SPH/SPH model for high speed orthogonal cutting of Al 6061-T6. Calamaz et al. [11] developed a 2D SPH/SPH model in order to predict the effect of tool wear in orthogonal cutting of Ti6Al4V alloy on cutting forces. Madaj [12] developed a 3D F.E. /SPH scaled-down model for orthogonal cutting of Aluminum alloy. All the forces results are then multiplied by the ratio between the real thickness and the developed model thickness. He used Johnson-Cook failure model and the minimum required strain for failure value in the model to predict accurate chip morphology. Xi [13] developed both 2D and 3D models to study the influence of workpiece initial temperature on the cutting forces while turning Ti6Al4V alloy. Because of a high resolution is required to predict the chip morphology, the 2D model was developed. However, the 3D model was developed in order to predict the cutting forces. Demiral [14] studied the influence of vibration parameters on the cutting forces while vibration-assisted turning of Ti6Al4V alloy. Xi et al. [15] developed a 3D model in order to study the effect of laser assistance while turning of Ti6Al4V alloy.

The work in which the forces are predicted using SPH and validated is very limited. Espinosa's model [10] underestimated the thrust forces by 30%, while Calamaz model [11] underestimated the thrust force components for different sets of Johnson-Cook parameters with minimum difference of 35% and maximum difference of 42%. However, they both used 2D models which do not consider Coulomb friction law and assumed that the tool velocity is ten times higher than the real velocity, which cannot be the case for thrust forces prediction. In order to predict the thrust force component, the simulation should run at the real machining conditions since the cutting speed significantly affect this component.

In the current study, a coupled thermo-mechanical study of a 3D face turning model is proposed using SPH technique. Johnson-Cook material constitutive model is used since it is well suited for simulating materials subjected to large strains, high strain rates, and high temperatures [16]. In order to get the model optimized, a further study on the effect of the friction coefficient and equation of state on the results was conducted. The results are validated by the experimental results in [17]. As mentioned earlier, no damage model has to be defined. However, using Johnson-Cook or Cockcroft and Latham damage models can be achieved by using the modified form of Johnson-Cook constitutive Model (MAT_107).

In the SPH method, the system is represented by a set of particles that carry the field variables and interact with each other particles within a range controlled by the smoothing length, Fig. 1. The SPH simulation problems can be obtained by solving the three conservative equations of the system along with the material constitutive law and equation of state. The first step in obtaining SPH formulation is representing the integral representation in the continuous form which is known as kernel approximation. The continuous form of kernel approximation is then discretized to finite number of particles [18].

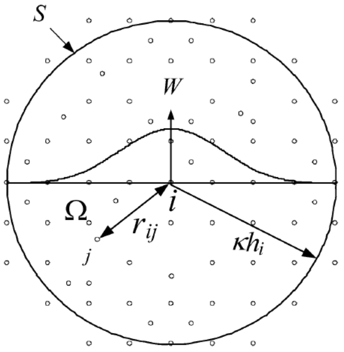


Fig. 1: SPH particle approximations in a two-dimensional problem domain. [18]

For any two particles in the domain i and j , the Kernal approximation of a function *f(x_i)* used in the SPH method is given by

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

W is the smoothing function, or weight function which is given by

$$W(x_i - x_j, h) = \frac{1}{h(x_i - x_j)^d} \theta(x_i - x_j) \tag{2}$$

Where *h* is the smoothing length which varies in time and space, and d is the number of space dimensions. The Kernel function should be a centrally peaked function. The most common auxiliary function used in the weighting kernel function is cubic B spline function θ(u), which is defined by

$$\theta(u) = \kappa \begin{cases} 1 - \frac{3}{2}u^2 + \frac{3}{4}u^3 & |u| \le 1 \\ \frac{1}{4}(2-u)^3 & 1 \le |u| \le 2 \\ 0 & |u| \ge 2 \end{cases} \tag{3}$$

Where u is the ratio between the distance between *i* and *j* to the smoothing length *h*, κ is the normalization constant that depends on the number of space dimensions. The higher values of κ make the region of influence larger; therefore, a higher computational time will be required. For finite number of particles N, the continuous form of Kernel approximation can be written in a discretized form as:

$$f(x_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W(x_i - x_j, h) \tag{4}$$

The SPH method is more accurate than traditional finite element packages where a considerable accuracy is lost because of the element distortion. No special meshing is required as in the Lagrangian approach that is mainly used for solid mechanics problems. Although the CPU time for the SPH is high as the creation of the shape functions is more time-consuming and is performed during the computation, the manpower time used in developing a model is lower [3]. Moreover, the SPH method can be used along with finite element techniques in order to reach a compromise between the accuracy and the computational time as will be presented in this paper.

3 Model description

3.1 Machining Conditions

Face turning of Ti6Al4V rods was performed by using uncoated tungsten carbide insert TPG432, with rake angle γ=-5, relief angle α=11, nose radius r_ε=0.8 mm, and tool edge radius r_β=25 µm. The experiments were conducted at cutting speeds of V_c= 55-90 m/min, feed rate of f= 0.01 mm/rev, and a depth of cut a_p=2 mm, Fig. 2. The three components of forces were measured with a force dynamometers on the turret disk of the CNC lathe [17].

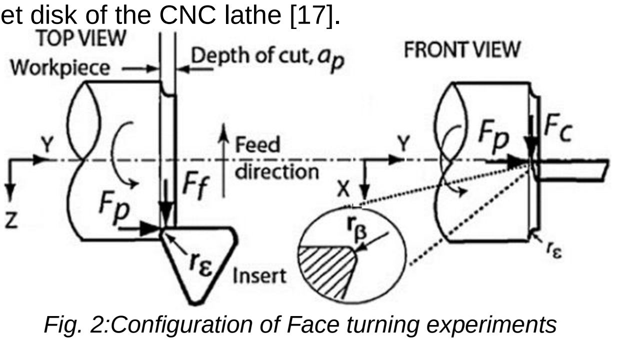


Fig. 2:Configuration of Face turning experiments

3.2 Model Assumptions

The tool is assumed rigid (*MAT_RIGID) and fixed in all directions except the cutting direction (x). On the other hand, the workpiece is fixed in all directions, Fig. 3. To model the workpiece, a hybrid model, which consists of SPH and F.E. parts, was used in order to reduce the computational time and the required memory to store the reaction forces data. The SPH method was used in the region where high deformation occurs, while a traditional Lagrangian mesh was used to simulate the material in regions with limited deformation. The spacing between the SPH particles is set to 50 µm in x and y directions, and to 25 µm in z direction. These values were selected from prior sensitivity analysis by the author and by Villumsen [9].

The contact algorithm *AUTOMATIC CONTACT_NODES_TO_SURFACE, in which the SPH particles set is the slave and the tool surface segment is the master, was used. The SST parameter in the contact card was set to 12.5 µm. A tied nodes-to-solid contact algorithm (*CONTACT_TIED_NODES_TO_SURFACE_OFFSET) is used to transmit the forces between the SPH and the F.E. parts. This approach was previously adopted in [13], [14] and [15]. However, the contact algorithms in LS-DYNA, which can be used for SPH, do not allow the heat transfer between the contacting parts. All the simulations were run to the real machining conditions and no mass-scaling or time-scaling were used. Furthermore, in order to avoid small time step, the artificial bulk viscosity option is not adopted in this model. The simulations were terminated once the steady state condition is achieved.

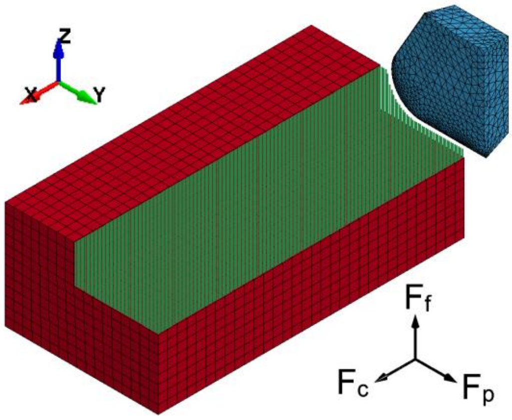


Fig. 3:SPH Model

3.3 Material Constitutive Model

Johnson-Cook material constitutive model (*MAT_JOHNSON_COOK) [16] represented in equation 5 is widely used to simulate the material behavior in machining modelling applications [19].

$$\sigma_{flow} = [A + B\varepsilon^n][1 + C\ln(\dot{\varepsilon}/\dot{\varepsilon}_o)][1 - (\frac{T - T_R}{T_M - T_R})^m] \qquad (5)$$

Where A is the initial yield strength, B and n represent the effect of strain hardening, C is the strain rate sensitivity constant, m is the thermal softening exponent, ε is the plastic strain, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_o$ is the reference strain rate, T is the workpiece temperature, T_R is the reference temperature, and T_M is the melting temperature.

For Ti6Al4V alloy, the density=4430 Kg/m^3, the modulus of elasticity (E)=114 GPa, Poisson's ratio is 0.3, A=870 MPa, B=990 MPa, C=0.008, n=1.01, m=1.4, T_M=1680 °C, T_R=25 °C, and the reference strain rate=1 s^{-1}[20].

In LS-DYNA, in order to accurately simulate the material behaviour using Johnson-Cook material constitutive model, an equation of state (E.O.S.) is required [21]. The E.O.S. is a mathematical description of the material behaviour. There are two types of E.O.S. can be used for solids; Gruneisen and Linear Polynomial [21] and [22]. It has been noticed in the literature that both E.O.S. are used in SPH machining modelling. In case of Ti6Al4V, the parameters of both E.O.S. are available. Therefore, a comparative study about the effect of E.O.S. on the results can be conducted in the current model since its effect was not studied in the literature. The simplified form of linear polynomial E.O.S. (*EOS_LINEAR_POLYNOMIAL) used in machining modelling in [9] and [12], is given by:

$$P = K\mu \qquad (6)$$

Where μ is the compression ratio, K is the bulk modulus [21]. This simplified form can be achieved by setting C1=K and all the other parameters to zero. The Gruneisen E.O.S. (*EOS_GRUNEISEN), used in machining modelling in [13] and [15], is given by

$$P = \rho_o C^2 \mu \frac{[1+(1-\gamma_o/2)\mu - a\mu^2/2]}{[1-(S_1-1)\mu - S_2\mu^2/(\mu+1) - S_3\mu^3/(\mu+1)^2]^2} + (\gamma_o + a\mu)E \tag{7}$$

Where C is the sound speed in the material, S_1,S_2 and S_3 are the coefficients of the slope of the shock speed versus the particle speed curve U_s– U_p, γ_o is Gruneisen gamma, a is the first order volume correction to γ_o, μ is the compression ratio, E is the internal energy, ρ is the current density and ρ_o is the initial density [21] and [22]. For the workpiece material, C=5130 m/s, S_1 =1.028, S_2= S_3=0, γ_o =1.23, and a=0.17 [23]. The different between both E.O.S. is shown in Fig. 4. It is obvious in the figure that the hydrostatic pressure is higher for the Gruneisen E.O.S. than the Linear Polynomial E.O.S..

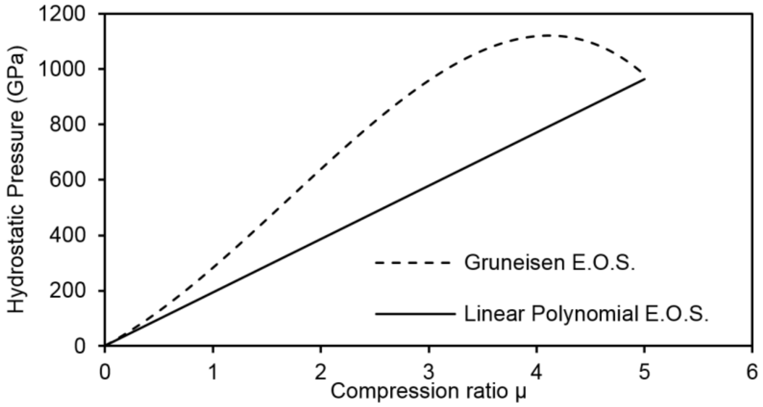


Fig. 4: The difference in the hydrostatic pressure values for both Gruneisen E.O.S. and Linear Polynomial E.O.S.

3.4 Friction model

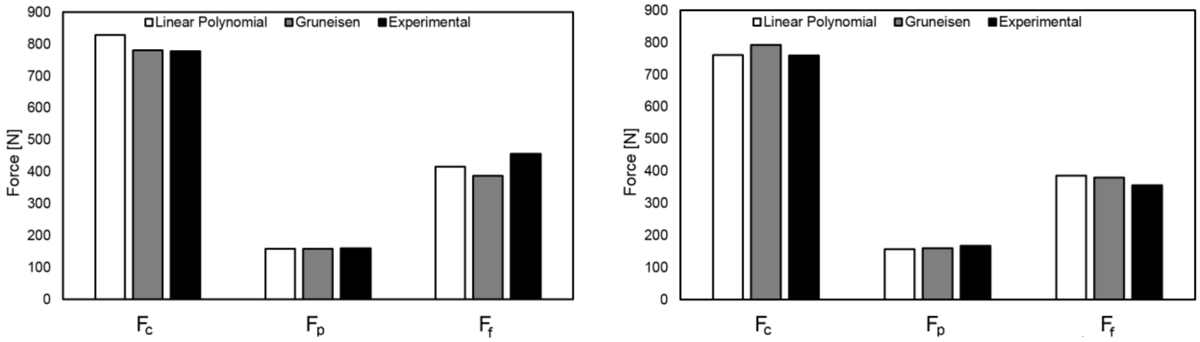
The effect of friction plays importance role in machining modelling. There are two friction laws available to be used with SPH; Classical friction law (Coulomb law) and non-classical friction law. In the current model, the simple Coulomb's law was considered on the whole contact zone even though its simplicity. However, it has been widely used in metal cutting simulations [19]. By using Coulomb law, the ratio between the thrust forces to the tangential force is assumed constant and represents a pre-defined value that represents the coefficient of friction μ [24]. The friction coefficient μ cannot be experimentally measured and there is no previous study found in literature on the effect of friction while using SPH in machining modelling at high friction coefficient values. Therefore, it was necessary investigate the effect of friction coefficient (μ) on the simulation results. Different friction coefficient μ values ranging from 0.1 to 0.7 were used in the proposed model. This approach was previously adopted in [25] in order to numerically determine the friction coefficient (μ) of the minimum difference between the predicted and measured cutting forces.

3.5 Thermal Parameters

The workpiece thermal parameters are defined in *MAT_THERMAL_ISOTROPIC card. For the workpiece material, the specific heat=546 J/Kg. °C, the thermal conductivity= 6.7 W/m-K, and the thermal expansion coefficient=8.70E-06 m/m.K. As mentioned earlier, when using SPH method, the heat transfer between the SPH part and the tool, or between the SPH part and the surrounding, is not allowed because of the nodal nature of the SPH particles. Therefore, the process is assumed adiabatic, which might affect the accuracy. However, this assumption can be valid for the proposed model as the thermal conductivity of the Titanium alloy is low and most of the heat is carried away by the chip. The fraction of plastic work converted into heat (FWORK) is assumed 90% [26]. The change in material properties as the temperature changes is neglected.

4 Results

Fig. 5 shows the predicted cutting forces for both E.O.S., compared to the experimental results. The results considered in the figure are the results with the least difference between the predicted and measured values. At cutting speed of 55 m/min, a difference of 7%, 1%, and 9% for Fc, Fp, and Ff respectively is achieved at friction coefficient µ=0.35 for linear polynomial E.O.S., and 1%, 1%, and 15% at friction coefficient µ=0.5 for Gruneisen E.O.S.. At cutting speed 90 m/min and friction coefficient µ=0.7, a difference of 0%, 6%, and 9% for Fc, Fp, and Ff respectively is achieved for Linear polynomial E.O.S., and of 4%, 4%, and 7% for Gruneisen E.O.S.. The chip formation of the analysis is shown in Fig. 6.



(a) V_c=55 m/min (b) V_c=90 m/min

Fig. 5:Comparison between simulation and experimental results

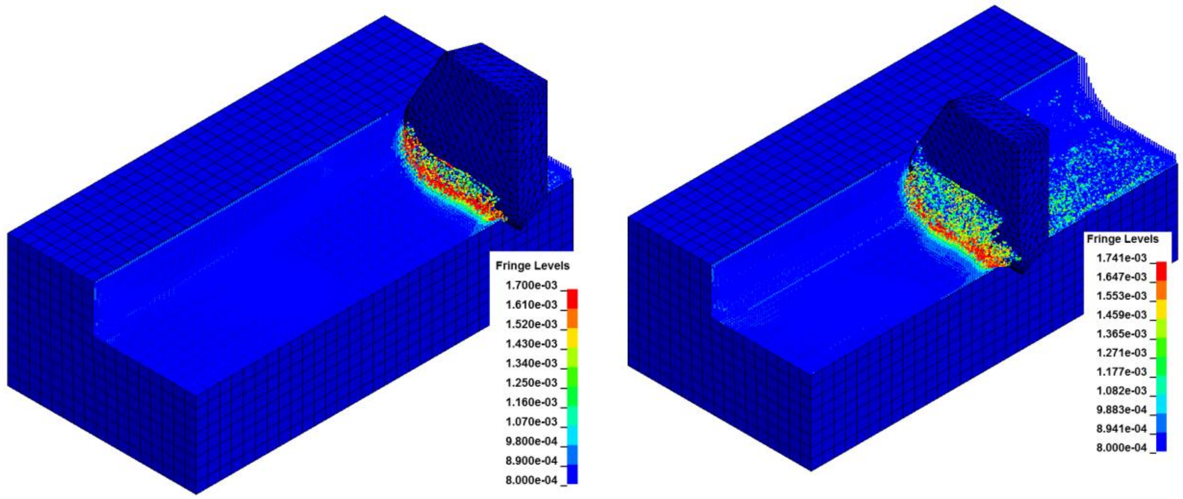


Fig. 6: Chip formation (Von-Mises stresses/10^{12})

Fig. 7 shows the influence of friction coefficient and the equation of state on the results. From the figure, it is obvious that there is no evidence that the equation of state type has a significant effect on the results and both have good predictions. However, the Gruneisen E.O.S. predictions are slightly higher than those of the Linear Polynomial E.O.S., which agrees with the hydrostatic pressure values in Fig. 4. In contrast, the friction coefficient value µ has a significant effect on the three components of force. However, at a friction coefficient of µ=0.7, a reduction of the cutting forces can be noticed, which cannot be the case for machining modelling. A possible reason of this reduction is that, at high friction coefficient values, some particles of the SPH part stick on the tool surface and do not allow the relative motion between the particles and the tool surface where they stick.

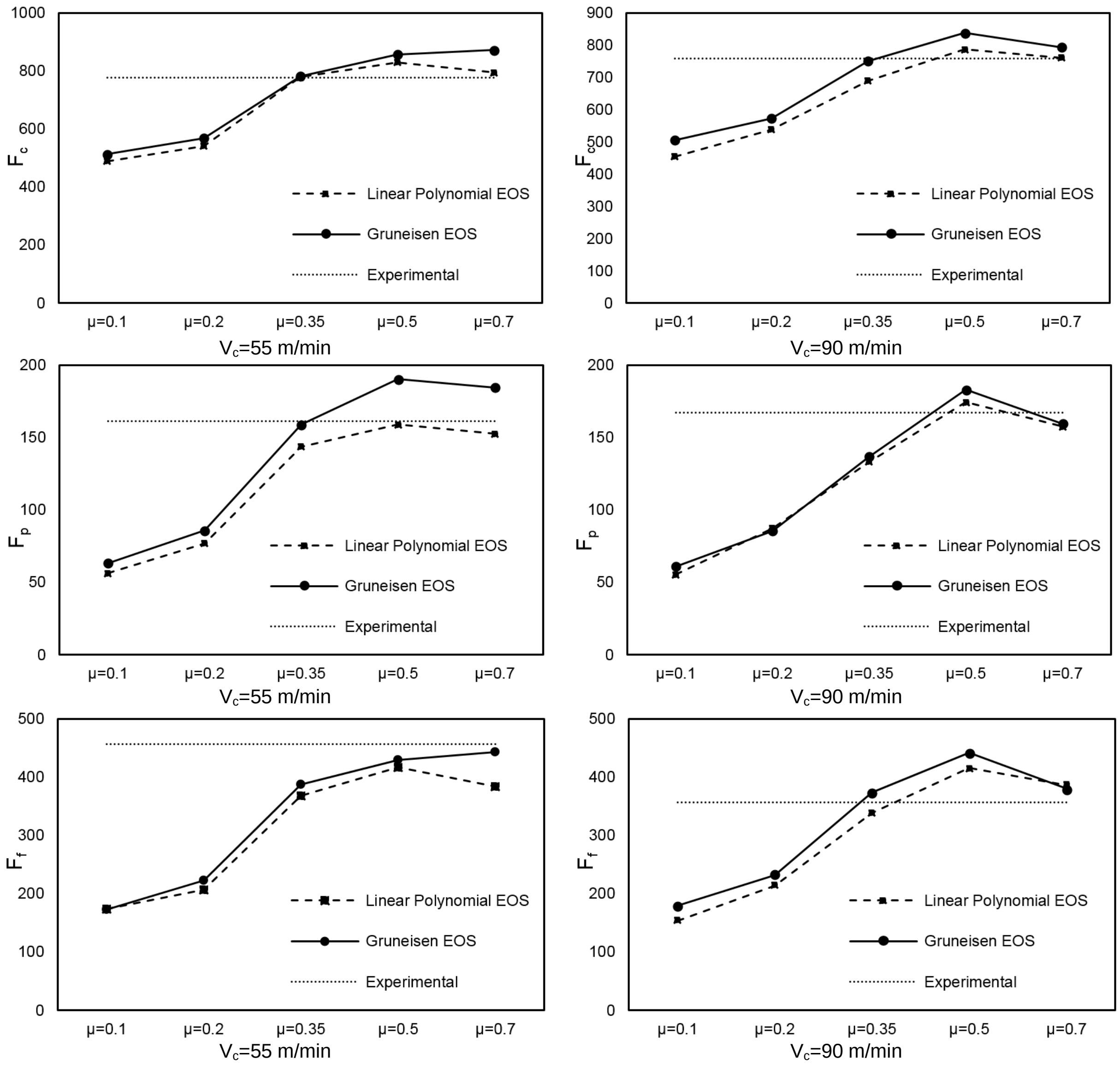


Fig. 7: The effect of friction coefficient and E.O.S. on the cutting forces components

5 Summary

- A 3D SPH/F.E. model was developed in order to predict the cutting forces while face turning of Ti6Al4V rods. The simulations results for the three components for forces find an excellent agreement with the published experimental results.
- The study proved that the equation of state type, whether it was Linear Polynomial or Gruneisen E.O.S., is insignificant on the results for the proposed model. However, the predictions of Gruneisen E.O.S. is slightly higher than the Linear Polynomial E.O.S. predictions.
- The coefficient of friction values is of significant effect on the results. Therefore, it should be accurately determined. Furthermore, a further investigation on the frictional behavior for contacts including SPH parts at high friction coefficients has to be conducted.

6 Acknowledgement

This research project is sponsored by ELARABY GROUP Graduate Scholarship to the Egypt Japan University of Science and Technology (E-JUST) and support of the Japanese International Cooperation Agency (JICA).

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