Investigation of Finite Element Modelling on Thin-Walled Machining of Ti6Al4V using DEFORM-3D

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Investigation of Finite Element Modelling on Thin-Walled Machining of Ti6Al4V using DEFORM-3D

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Abstract. Ti6Al4V is one of material that difficult to be machined, and the machining process on thin-walled is also a challenge by the manufacturer. In order to avoid error in thin-walled machining, the FEM simulation using DEFORM-3D is conducted to acquire characteristic along the thin-wall. Dynamic deformation will be presented as stability of thin-wall, which is depicted in movement of the point tracking. As validation in this investigation, the experiment was conducted with 42-degree helical end-mill, which is connected to dynamometer that is obtained the cutting force value. The results showed that the FEM-simulation is failed to approach the experimental results. Some of the suspected reasons are the occurred unpredictable vibration, too small depth of cut.

1. Introduction

Titanium application is most significant in jet engine and airframe components, and for other critical structural parts, these components have the characteristics of a thin-wall monolithic part [1][2]. Aircraft components shape thin wall such as flap track, pylon, components, spars/skins/ribs/frames, main landing gear beam. Thin wall machining is generally defined as the machining of the thin wall using a specific height to depth ratio (approx. 15:1) and wall thickness (approx. 3-5 mm). The definition of thin wall component is based on dimensional accuracy. A thin wall component is where elastic deformation of the wall is larger than or equal to the allowed tolerance requirement and can be written as; **$\delta \geq T$, where δ is the elastic deformation of the wall and T is the allowed machining** tolerance. The study of resulting surface errors when machining a thin-wall monolithic component is crucial to increase the part accuracy and productivity [3].

The surface quality and homogeneity microstructure are difficult to be achieved from the additive manufacture process caused invisible defect inside thin-walled such as porosity, inclusion, and unmelt powder. However, the machining process of thin-walled Ti6Al4V not as easy as thought, low thermal conductivity lead the tool-chip sticking in cutting tool [5,6] and low modulus elasticity affected in lobes stability that made tool jumps out from cutting zone caused by self-excited vibration (chatter) [6,7].

A considerable in cutting process parameters such as helical angle, feed rate, depth cut and cutting speed, even adding an object (layer) as a damper [8,9] or clamped has been conducted to aims reduced errors in machining [10–12]. The evaluation to change from the experiment (physical modelling) by machining into simulation modelling analysis has been conducted in several investigations; this aims

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to reduce cost by trial and error [13–16]. The forecasting uses finite element modelling (FEM) simulation is the flexible observation until it has obtained the optimum parameter.

In previous studies, the milling process has been conducted in one revolution or less used DEFORM-3D software, where the cutting tool movement in the rotation without translation movement (feed rate) [17–19]. The milling process along of thin-wall has been conducted in other studies, where the result just been taken on many time from cutting start that is aims to predict cutting force or temperature effect [2,20]. However, the stability machining process along thin-walled has to be considered, which represents a comparison machining process with another machining process.

In define stability of the thin-walled, several studies about dynamic deformation has been conducted with several methods from analytic and experimental, i.e. FRF analytic prediction, sound measurement [21], laser displacement sensor [22], PVDF thin-film sensor [23]. In this paper, the dynamic point deformation will be presented as an alternative in analytic stability of thin-walled with FEM simulation using DEFORM-3D software. The point tracking is placed along thin-wall that is depicted with the dynamic point movement during machining process, where the tight accuracy of the point and times interval can be assigned according in demand analysis.

2. Research Methodology

2.1. Experimental setup

Experimental setup (physical modelling) aims to validate the FEM-Simulation result, where the experiment of thin-walled Ti6Al4V used CNC MAHO DMC 835 V and the magnitude of cutting force F_X , F_Y and F_Z was achieved from a dynamometer Kistler type 9625B, which was connected to amplifier Kistler type 5019 that transferred to a computer, as shown in **Figure 1** (A).

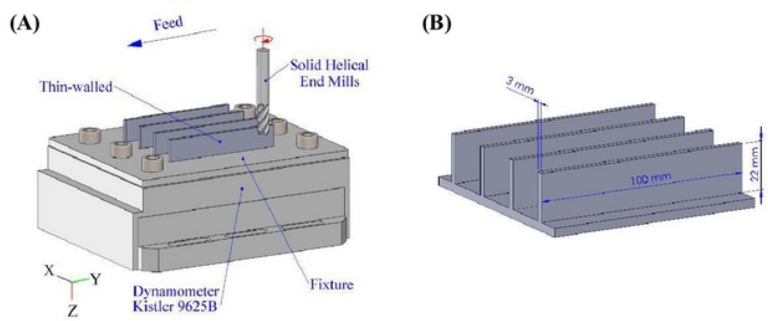

Figure 1. (A) Experimental setup end-milling of thin-walled Ti6Al4V; **(B)** Geometry of thin-walled

The cutting process used the uncoated helical end-mill tool Carbide WC-Co (SECO-HPMT) with 42-degree helix angle, 4 flutes and diameter of 10 mm. The thin-walled (workpiece) used titanium alloy Ti6Al4V grade 5 (equivalent to ASTM 381) with geometry as shown in **Figure 1** (B).

2.2. FEM-Simulation setup

Before conducting FEM-Simulation, the tool used in the experiment was redrawn according to the geometry delivered in a tool catalogue using CAD software SolidWorks. The result of SolidWorks is formatted in STL file format extension. After this process, the redrawn end-mill must be converted to KEY file format extension, to be compatible to FEM-Simulation software DEFORM-3D.

The milling simulation was applied in DEFORM-2D/3D Pre-Processor, where the limitation features on 3D-Cutting Pre-Processor in input the machining simulation parameter. The object is imported then assign type as elasto-plastic (thin-walled) and rigid (end-mill), then the end-mill cutting set as a primary die. Material selection was obtained from the software library, thin-walled used Ti6Al4V-machiningSFTC and end-mill used WC.

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In this study, the deformation in the machining process is to be analysed along thin-walled. Furthermore, the depth of cutting in axial 7.07 mm and radial 0.32 mm have been set using object positioning which regulates the tool and workpiece position. The uncoated tool under MQL usin
coconut oil are used for heat transfer control in the simulation parameters, the temperature at 25ºC is assigned to environment and tools then the convection coefficient coconut oil at cutting speed 100 m/min in value 0.9254 N/sec/mm/C [24]

The magnitude mesh element and element size affected into simulation result, the meshing is used tetrahedral mesh type with relative element magnitude in value 300.000 elements with size ratio 10 on the thin-walled, and the mesh was controlled into cutting surface area for refining element size with value 0.01 size ratio in element outside windows, as shown in **Figure 2** (A). On the weighting factor parameter, the value strain and strain rate distribution set on value 0.5 respectively, then for other parameters set on zero value. The lousy element shape and plastic deformation on simulation made the process to be aborted caused the element has to be distorted, which led to negative Jacobian. On DEFORM-3D, the distortion element is replaced into new element used remeshing element method with the local element re-mesh method on the relative interference depth value 0.001.

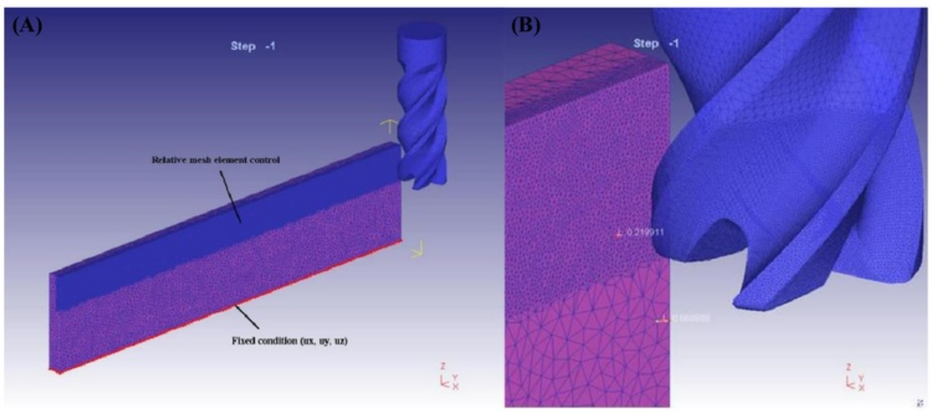

Figure 2. (A) Boundary and mesh condition simulation in thin-walled;
(B) Element size measurement

The absolute mesh is better than the relative mesh element control size, but the limitation the DEFORM-3D software provide element above 500.000 elements made the thin-walled element size cannot reach with estimation size as shown in **Figure 2** (B), and therefore the remeshing method is used to help this problem.

The object movement was assigned into end-mill with translation and rotational movement. Otherwise, thin-wall made as a fixed condition on the bottom surface of thin-walled. The speed type was chosen with a constant value in 33.546 mm/sec for end-mill translation movement (feed rate) and the rotation movement with constant angular velocity in value 3184.713 rpm.

Simulation control regulated the main simulation parameters. The Lagrangian incremental formulation type was assigned in this process, where the plastic deformation in machining made element distortion, and this element will be regenerated (re-mesh). Furthermore, the step magnitude has to be calculated by considering several factors such as element size, feed/tooth, and length of thin-

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walled. In this study, the element size is obtained from half value of feed/tooth in value 0.158 mm/tooth, which is estimated the element size is 0.075 mm.

In DEFORM-3D simulation, the time and distance magnitude per step are set manually as a domain. In the simulation process, theses step value changed automatically according to the magnitude of the element contact between end-mill and thin-walled. The calculation of step increment aims to predict the magnitude step along thin-walled, the improper calculation of step increment made the machining process stopped in undesired condition [25]. After the step incremental size is obtained, then the magnitude of step prediction along thin-wall is also obtained by calculating the length of the milling process, where cutting length is set 110 mm and cutting time 3.279 second then the magnitude step is predicted about 300 steps in one revolution/second. The time 0.01884 second is achieved for one revolution, which this value will be divided with 300 step and obtained 6.28e-05 second/step.

The iteration solver used Sparse and Newton-Raphson iteration method as default deformation simulation control. The maximum iterations are set to the value 200 iterations per deformation step. The contact condition relation between master (tools) and slave (workpieces) are set in inter-object parameter, where the Coulomb friction set at value 0.2 in according several investigation contact Ti6Al4V with WC in lubricant process [26]. However, several value has been used in other investigation in defined heat transfer interface value between Ti6Al4V and WC with value 1000 $kW/m^2.K$ [27], 2000 $kW/m^2.K$ [28], 10 $kW/m^2.C$ [29] and 83 N/sec/mm/C [30], the improper in defined heat transfer coefficient value because the contact between solid component is not convection, it is actually conduction unit. In DEFORM-3D software manuals book has been explained for the condition without convection, it can be entered value 0.004(English) or 11(SI).

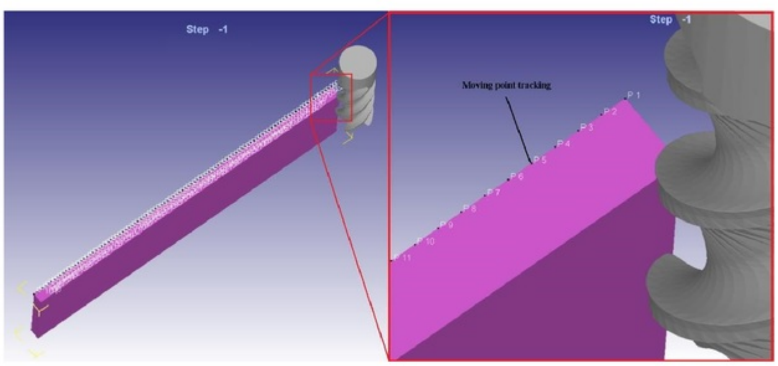

Figure 3. Point tracking displacement calculation along thin-walled Ti6Al4V

The prediction force value from simulation with experiment from many investigations has been explained from other studies. In this study tried to compare flow stress methods used tabular data format Ti6Al4V-machiningSFTC from material library with the parameter from the Johnson-Cook flow stress, which is expressed by equation 1.

$$\sigma = \left(A + B\varepsilon^{N}\right)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_R}{T_M - T_R}\right)^{M}\right] \quad (1)$$

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Where yield strength parameter denoted as A , the hardening modulus B , the strain rate sensitivity coefficient C , the hardening coefficient N , the thermal softening coefficient M , equivalent strain ε , strain rate ε , reference strain rate ε_0 , and T , TR ,TM is denoted as temperature of operation, room, and melting respectively. Furthermore, the value of the Johnson-Cook has been obtained and validated by two investigation that recommended the parameter value as shown in **Table 1** [31,32].

Table 1. The recommended parameter of Johnson-Cook flow stress prediction by other investigations

Set	A (MPa)	B (MPa)	C	n	m	
1 [33]	968	380	0.0197	0.421	0.577	^{0} 0.1
2 [34]	997.9	653.1	0.0198	0.45	0.7	1

The contrary prediction value between two parameters set in Table 1 that was used by other studies. The different value will be obtained in same parameter if the step magnitude and element size are assigned not correctly.

In DEFORM-2D/3D post processor, the cutting force resulted from simulation will be obtained and compared with experimental value as validation. The deflection value along thin-walled is obtained from point tracking by converting step domain into length domain. The point tracking is placed along thin-walled according to the accuracy in data measuring. The point tracking set with 101 points (P1, **P2… P101**) along 100 mm in thin-walled, where the range point accuracy is obtained until 1 mm as shown in **Figure 3**. This analysis aims to determine the dominant effect between the force or lobes stability in the contribution of the deflection effect.

3. Result and discussion

The simulation thin-walled using DEFORM-3D software is difficult due to the comparison of the size of thin-walled with feed and depth cut size that made the significant ratio in element size. Generally, several investigations used small component (workpiece) in DEFORM-3D simulation and single movement (translation or rotation), where the chip formation is generated easier. The unpredicted chip formation in this study, where the simulation used the relative remesh element size and complex geometry of the helical end-mill.

In addition, several parameters must to be set in DEFORM-2D/3D Pre-Processor, where the value 0 of FUTHER_IMPROVE_CONTACT_ELEMENT in LOCAL_REMESH.DAT file is set to 1. The file STRAIN_RATE_DST.DAT and STRAIN_DST.DAT must be created manually that will be placed in folder directory. The elasto-plastic and dynamic displacement of thin-walled made the process stopped in improper step during simulation process. The problem is caused remeshing process cannot encounter in element contact or smaller time step is required. To solve this problem, the fracture condition of Cockcroft -Latham (C-L) parameter is set to value 0.6 [35], but the disadvantage of this parameter cannot generate chip formation then the C-L fracture condition was set to value 0, which chip formation able to be generated

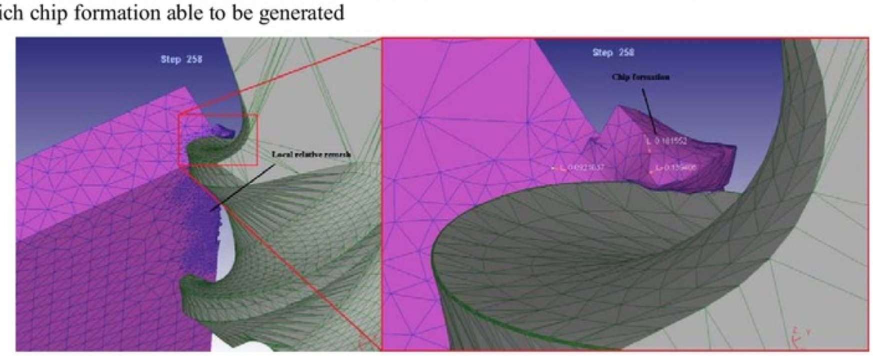

Figure 4. Chip formation in local relative remesh and element size quality

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As described in **Figure 2** (B), chip formation is able to be generated if the element size smaller than feeding value. In **Figure 4**, relative remesh has been generated element size until 0.09 mm, which smaller than initial element size. The simulation in investigation of Ti6Al4V thin-walled used DEFORM-3D software focus in dynamic deformation response along thin-walled. The result discussion is limited in the x-axis parameter.

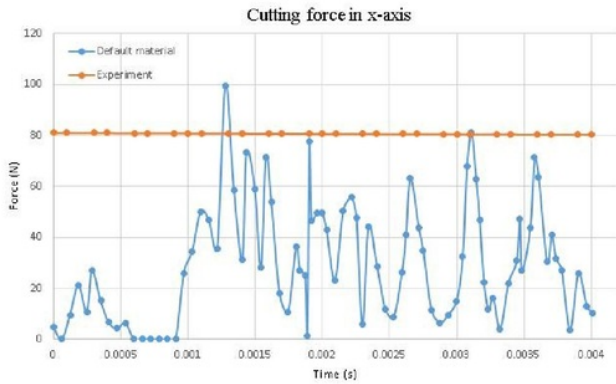

Figure 5. The comparison cutting force in x-axis between experimental and simulation using default material Ti6Al4V-machiningSFTC

Depicted in **Figure 5**, the result of the force between experimental with simulation was taken from time tool contact the workpiece. The fluctuation of result in simulation caused several factors, which the distinction of the time range.

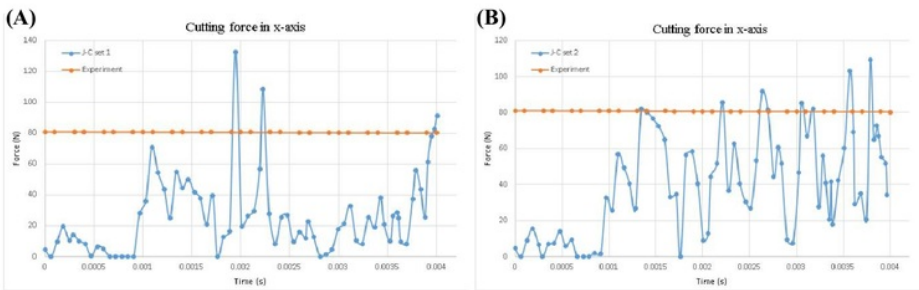

Figure 6. The comparison cutting force in x-axis between experimental and simulation using Johnson-Cook, **(A)** Set1 parameter value; **(B)** Set 2 parameter value.

From result of cutting force, the Johnson-Cook in parameter set 2 showed more significant result with experiment result. This result as a validation to continue the calculation in dynamic displacement along thin-wall, but this value not able to be used as prediction because the value is further from the expectation result. However, this study tried to giving a new approach in dynamic displacement of thin-walled, then this value is used as the result of dynamic displacement that is shown in **Figure 7**.

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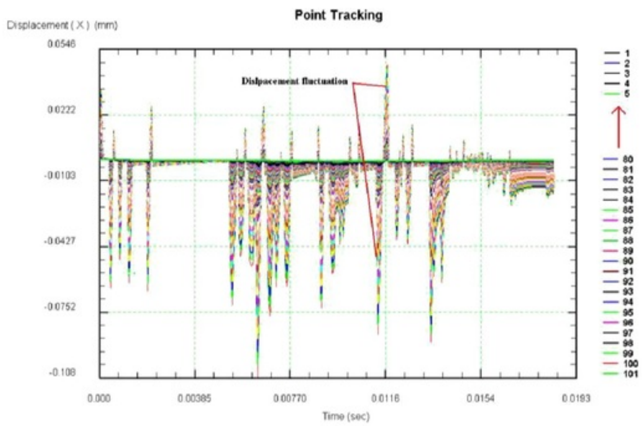

Figure 7. Dynamic displacement result along thin-wall used 1- 101 points tracking in x-axis

The dynamic displacement value from points tracking showed the undesired condition, the displacement value is further from the cutting tolerance. The fluctuation displacement is caused elasto-plastic behaviour ofs thin-walled, the negative value of displacement is caused by cutting force and positive value displacement of point tracking is caused by self-excited force, which is direction toward to cutting edge.

4. Conclusion

It has been proven that the finite element simulation resulted is further accuracy compare to the experimental result. The force result as a prediction to validate the deflection value, where the method can be used as a reference in the further study of thin-walled deflection with several parameters. The preliminary study of point tracking in dynamic deformation measurements using DEFORM-3D, where the simulation can predict the quality surface roughness and error in the machining process. In order to requisite on the optimisation of the machining process for reduce production cost caused by trial and error.

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