Effects of cutting conditions on the cutting forces in machining additively manufactured Ti6Al4V alloy

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Abstract. Machining of additive manufacturing (AM) process results in excessive consumption of the cutting power due to the high strength and hardness of the material produced that led to high cutting forces and short tool life during machining process. This paper aims to investigate the effect of cutting conditions and coefficient of friction on the cutting forces, during finite element analysis (FEA) of an orthogonal cutting of AM Ti6Al4V alloy bar. The FEA simulation considers three different experiments at low, medium, and high cutting conditions. The result shows that as the depth of cuts gets deeper and the cutting speed increases, the cutting forces were found to increase, leading to serrated or segmented chips formation. A cutting force of 1300.36N was observed at a cutting speed of 150 m/min and a coefficient of friction of 0.9. The cutting force was found to be weaker at the higher shear plane angle of 42.2° and higher at a smaller angle of 37.57°. The coefficient of friction was observed to be insignificant at lower value of 0.09 and was seemed to affect the cutting force at value around 1.

Keywords:
Additive manufacturing, SLM, FEA analysis, cutting forces, and Johnson cook parameters.

1 Introduction

Additive manufacturing (AM) also known as 3D printing is a breakthrough method for producing three-dimensional objects. AM creates parts from the ground up, providing a unique degree of design freedom and flexibility, in contrast to standard subtractive manufacturing techniques, which entail removing material from a solid block. Compared to traditional manufacturing techniques. AM has several benefits, such as on-demand production, complicated geometries, customization, fast prototyping, and less material waste [1]. FEA simulation shows a good agreement between experimental and simulated results of flow stress obtained with an error of less than 4% [2]. The high temperature may cause the cutting edge to dull quickly since it is near the cutting zone, where the temperature is higher [3]. When comparing the Ti6Al4V alloy produced by the selective laser melting (SLM)

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process to the Ti6Al4V alloy manufactured conventionally, increased feed rates and cutting speeds lead to an inferior surface finish [4]. This is due to the SLM process using materials with higher strength and hardness, which affect the materials' plasticity. Due to significant mechanical and thermal loads during the manufacturing process, the SLM technique yields products with comparatively large residual stresses [5]. More frequent chip segmentation results from high cutting rates, particularly when machining Ti6Al4V alloy [6]. It was observed that during the turning operation of Ti6Al4V alloy manufactured by the SLM process, the high cutting speed and feed rates led to high cutting force and poor surface finishing [7], [8]. FEA analysis was reported using a modified J-C model on a refractory Ti6Al4V alloy to investigate the effects of material behaviour on chip morphology and cutting forces. The results material property of 0.11 gave the best-simulated chip morphology, but the cutting forces were not sensitive to the friction coefficient between the tool and the refractory titanium alloy [9].

Several studies [10], [11] have used different approaches to achieve optimal process parameters to overcome challenges in manufacturing. Machining processes as a result also require investigations to analyse the effect of cutting parameters on the machining responses. Study shows that specific cutting energy was reduced by 6% in turning of Ti6Al4V alloy at optimum cutting conditions of 150 m/min cutting speed, 2 mm depth of cut, and 0.20 mm/rev feed rates [12]. Another report shows that machining Ti6Al4V alloy at a low cutting speed of less than 60 min/min leads to a decrease in cutting force due to built-up edges, whereas at a cutting speed of more than 60 m/min, the cutting forces were found to be increased because no built edge formed [13]. This research focuses on the FEA analysis to investigate the effects of cutting conditions and coefficient of friction on the resulting cutting forces of AM Ti6Al4V alloy using orthogonal dry machining.

2 Materials and Method

The material used in this research is Ti6Al4V alloy. ANSYS software was employed for the simulation with Johnson Cook strength parameters as shown in The cutting force and shear plane angle can be determined from equations 1 and 2 respectively, while equation 3 represents flow stress from the Johnson-Cook model parameters.

$$F_C = R\,cos(\lambda + \phi - \alpha) \tag{1}$$

$$tan\phi = \frac{r\cos\alpha}{1 - \sin\alpha} \tag{2}$$

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left(1 + C\,ln\frac{\bar{\varepsilon}}{\bar{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)^m\right] \tag{3}$$

Table 1. The tungsten carbide tool was selected considering its ability and wide usage to machine hard-to-cut material like titanium alloy with properties as shown in

Table **2**. The cutting force and shear plane angle can be determined from equations 1 and 2 respectively, while equation 3 represents flow stress from the Johnson-Cook model parameters.

$$F_C = R\,cos(\lambda + \phi - \alpha) \tag{1}$$

$$tan\phi = \frac{r\cos\alpha}{1 - \sin\alpha} \tag{2}$$

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left(1 + C\,ln\frac{\bar{\varepsilon}}{\bar{\varepsilon}_0}\right)\left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)^m\right] \tag{3}$$

Table 1: Johnson Cook strength parameters.

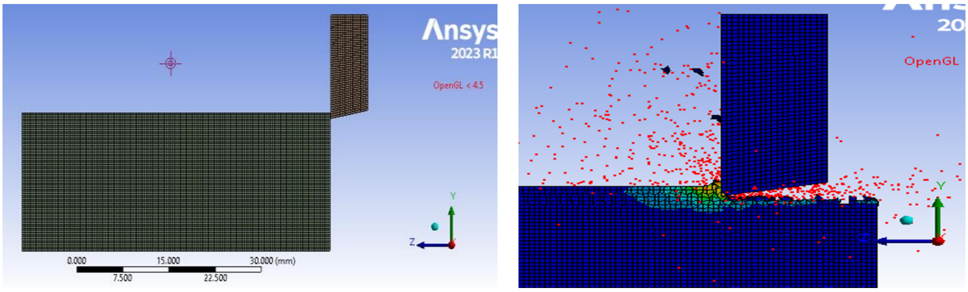
A	B	C	n	M	T_o (°C)	$T_{melting}$ (°C)
1000	780	0.033	0.47	1.02	20	1599.9

The workpiece was manufactured by the SLM-AM process obtained from a published article. Single-point orthogonal dry machining was performed on the workpiece and tool with their properties as represented in **Error! Reference source not found.** Figure 1 shows meshing and the discontinuous chip formation at 150 m/min.

Table 2: Workpiece and cutting tool properties.

Material property	**Workpiece (Ti6Al4V alloy)**	**Cutting Tool (Cemented Carbide)**
Density (Kg/m^3)	4405	14,800
Ultimate tensile strength (MPa)	951	2950
Modulus of elasticity (GPa)	110	651
Thermal Conductivity (W/Mk)	6.7	58.85
Poison ratio	0.33	0.29
Heat Capacity (J/KgK)	562	15.002

Three simulation experiments were conducted at low, medium, and high cutting conditions with the properties shown in Table 2 Cutting speeds are 50, 80, and 150 m/min; the depth of cut is 0.5, 0.8, and 1.0 mm. The tool geometry is rake 0, clearance angle 11°, tool edge radius 0, a width of cut 3.0mm, and the workpiece is 50mm x 20mm.



(a) (b)

Figure 1: (a) Workpiece and tool meshing (b)2D FEA model with a discontinuous chip formation at 150 m/min.

3 FEA Simulation Results and Discussion

Cutting Force

The FEA analysis shows the comparison between the cutting forces and cutting speed shown in Figure 2. The simulation results demonstrate that the cutting forces continued to deteriorate as the cutting circumstances kept increasing. decreased cutting conditions led to the observation of a decreased cutting force. It is evident that when the cutting conditions seemed to go higher, the cutting force was found to become higher [7].

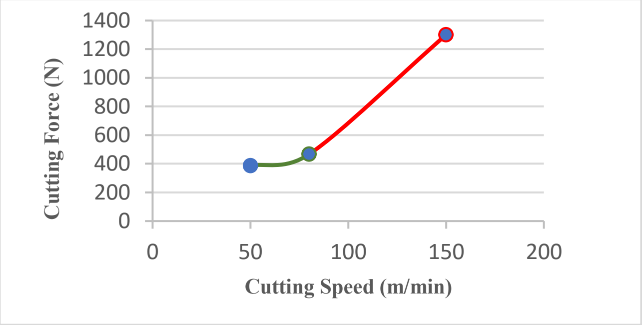


Figure 2: Cutting force against cutting speed.

Figure 3 represents at shallow depths between 500 to 800 the cutting force was very weak, however at deeper depths about 1000 um or more the cutting force became higher, which means a lot of strain energy was consumed.

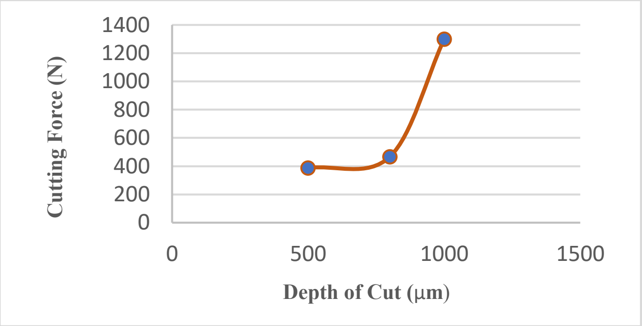


Figure 3: Cutting force against depth of cut.

The coefficient of friction shows insignificant effects on the cutting force at a lower value but seems too significant at a higher value of 1 or more as seen in Figure 4.

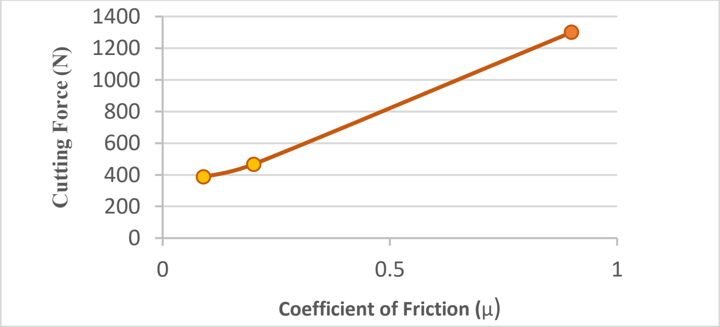


Figure 4: Cutting force against coefficient of friction.

At the lower shear plane angle, the cutting force was observed to be higher and tend to be weaker at the larger shear plane angle as can be seen in Figure 5. These effects of the shear plane angle were supported by different researchers, for example, a high cutting speed in turning of Ti6Al4V alloy leads to more frequent chip segments [6], also an increase in feed rates leads to an increase in a shear plane angle which results in a decrease in energy consumption in the machining of Ti6Al4V alloy [14], [15]. Specific cutting energy was found to be reduced by 6% in the optimization of turning Ti6Al4V alloy [12].

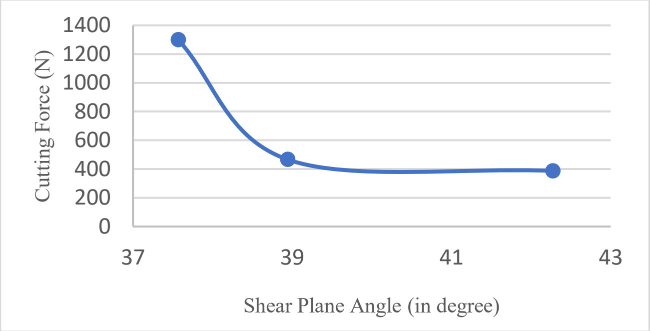


Figure 5: Cutting force against shear plane angle.

4 Conclusion

The conclusion of FEA simulation results as represented from Figure 2 to Figure 5. summarises the following:

The cutting force increases as the cutting condition increases; this leads to high consumption of the cutting energy. It also shows that as the tool gets deeper it affects the cutting force negatively.

Cutting Ti6Al4V alloy at a depth of cut of more than 1000um produced from the SLM process results in a higher cutting force of 1300N, which will also affect the tool life.

Coefficient of friction was insignificant at a lower value of 0.09 but found to be significant at a higher value around 1, which results in a cutting force of 1300.36N

The cutting force was found to be weaker at higher shear plane angles and higher at smaller angles.

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